TRANSVERSE FORCES ON SMOOTH AND ROUGH CYLINDERS IN HARMONIC FLOW AT HIGH REYNOLDS NUMBERS

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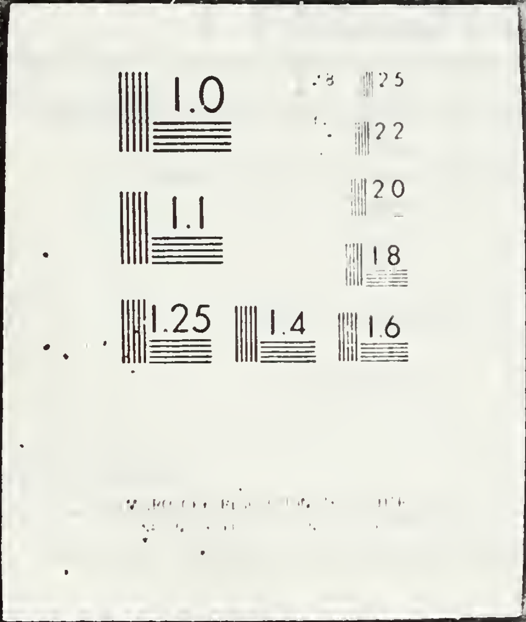

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NAVAL POSTGRADUATE SCHOOL

Monterey, California

THESIS

TRANSVERSE FORCES ON SMOOTH AND ROUGH CYLINDERS
IN HARMONIC FLOW AT HIGH REYNOLDS NUMBERS

by

Neil Jon Collins

June 1976

Thesis Advisor: T. Sarpkaya

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The lift coefficient and the frequency of the alternating force have been determined. For smooth cylinders, the lift coefficients were found to depend on both the Reynolds and the Keulegan-Carpenter numbers

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It is recommended that the experiments be extended to the self-excited hydro-elastic oscillations of cylinders in harmonic flows.

Transverse Forces on Smooth and Rough Cylinders

in Harmonic Flow at High Reynolds Numbers

by

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B.S., University of Massachusetts, Amherst, 1969

Submitted in partial fulfillment of the
requirements for the degree of

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It is recommended that the experiments be extended to the self-excited hydro-elastic oscillations of cylinders in harmonic flows.

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NOMENCLATURE

A	Virtual amplitude of the motion
A_i	Amplitude of the motion
a_m	Maximum acceleration
CLMAX	Maximum transverse force coefficient, also used as C_L(max)
CLRMS	Root-mean-square transverse force coefficient
D	Diameter of the test cylinder
F	Instantaneous total force acting on the test cylinder
f_r	Frequency ratio, $f_v/1/T$
f_v	Frequency of the first harmonic of the transverse force
F_m	Measured force
g	Gravitational acceleration
H	Distance between pressure taps and mean water level
K	Keulegan-Carpenter number
L	Length of the test cylinder
Re	Reynolds number
k	Sand roughness particle size
s	Distance between the pressure taps
T	Period of oscillations
t	Time
U_m	Maximum velocity
u	Instantaneous velocity
w	Width of the test section
β	Frequency parameter
γ	Specific weight of fluid

ΔP	Differential pressure
θ	Phase angle
ν	Fluid kinematic viscosity
ρ	Fluid density

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The author wishes to thank Professor T. Sarpkaya for suggesting the research topic and for his guidance throughout the investigation, from its inception to the completion of the final manuscript. It has been said about research that it provides:

> " A unique opportunity to inquire,
> but a rarer occasion to understand."

Professor Sarpkaya fully exemplified these words. The author will always be grateful for his undying enthusiasm, belief, quick-wittedness, effervescent nature, and friendship throughout this project. It has been a great honor to know and work with such a man.

Also, it is a pleasure to thank Mr. J. McKay of the machine shop of the Department of Mechanical Engineering who possesses the unique ability to transform ideas and sketches into workable hardware much of which was utilized in the test facility.

Also, it is desirous to extend my thanks to the Ponticelli family for "adopting" me and making my stay here that much more pleasant.

Finally, the author wishes to thank his parents for their continued faith in him not only throughout this project, but throughout life itself, as one of God's greatest gifts is understanding and loving parents.

I. INTRODUCTION

Information about the time-dependent forces acting on bluff bodies in general and circular cylinders in particular has considerable practical interest in ocean and wind engineering, as well as in basic understanding of fluid mechanics. Extensive discussion about the flow-induced forces and oscillations exists in the literature, but the basic hydrodynamic data are lacking, particularly at higher Reynolds numbers which are of current practical interest.

Much of the present knowledge on the hydrodynamics of the oscillatory flow about the cylinders has been obtained by means of model tests in wave channels at Reynolds numbers generally two to three orders of magnitude smaller than prototype Reynolds numbers. These model tests, which have been primarily concerned with in-line forces, have disclosed that the drag and inertia coefficients may be correlated with the amplitude of the motion relative to a characteristic dimension of the body and that the effect of the Reynolds number is obscured by that correlation. The field data have shown rather large scatter and no systematic correlation with either the relative amplitude or the Reynolds number. Understandably, there is considerable controversy in the literature regarding the effect of viscosity, free surface, etc.

Vortex shedding gives rise to an alternating force in both steady and time dependent flows. In spite of the considerable interest, however, the transverse force or the lift force in harmonic flow received very little attention. Recently, it became clear from the observations of the

oscillations of long piles and strumming of cables that the lift forces are important not only because of their magnitude but also because of their alternating nature which under certain circumstances may lead to the phenomenon known as lock-in or vortex synchronization. This phenomenon may cause failure due to fatigue and increased in-line force. Obviously, the total instantaneous force acting on the structure is increased by the lift force and modified by the oscillations of the body. This increase refers to the vectorial sum of the in-line and transverse forces and not to the forementioned oscillations in the in-line force due to vortex shedding.

Some of the previous studies include those carried out by Chang [1], Bidde [2], Wiegel and Delmonte [3], Mercier [4], Sarpkaya and Tuter [5], Jones [6], Isaacson [7], and Sarpkaya [8]. Bidde [2] dealt primarily with the ratio of the transverse force to the in-line force in many flows and concluded that the lift force behavior is primarily dependent on the Keulegan-Carpenter number rather than upon the Reynolds number and that the predominant lift frequency is twice the wave frequency. Bidde's data are difficult to interpret because of the fact that the Reynolds number and the Keulegan-Carpenter number were calculated in terms of some average value, that the force measured was the total force on the complete length of the pile, and that the submerged end of the vertical cylinder was completely free to generate a complex three dimensional flow and influence the vortex shedding.

Wiegel and Delmonte [3] extended Bidde's work and used the Keulegan-Carpenter number based on the wave-surface kinematics. They have in general confirmed Bidde's conclusion except for the fact that the lift frequency was irregular and varied from about 1.3 to 6 times the wave frequency.

Sarpkaya and Tuter [5] measured the transverse force on cylinders in plain harmonic flow at relatively low Reynolds numbers and found that the maximum lift coefficient is primarily a function of K and that it can acquire large magnitudes near Keulegan-Carpenter numbers of 15. This work was subsequently extended to cylinders in the vicinity of a plain wall [6] and to higher Reynolds number flows [8].

Isaacson [7] measured the lift force on vertical cylinders in wavy flows within a Keulegan-Carpenter range of about 0 to 25 for intermediate depth waves. The Reynolds number range covered was from about 100 to 5000. Isaacson concluded on the basis of his and others work that lift was dependent both on the Reynolds and Keulegan-Carpenter numbers and that the dependence of the lift coefficient on the Keulegan-Carpenter number was considerably stronger and tends to obscure the weaker dependence on the Reynolds number. He also argued that for higher values of the Keulegan-Carpenter number the predominant lift frequency must increase with the Keulegan-Carpenter number.

It is apparent from the foregoing that both the in-line and transverse forces on the structures in the marine environment must be evaluated with proper attention to the order of magnitude of the Reynolds and Keulegan-Carpenter numbers. Furthermore, one must take into consideration the surface conditions of the structure such as rigid and flexible marine growth. There is not at present either sufficient or reliable data to answer the needs of the designer and to isolate the influence of the individual factors on the variation of the force transfer coefficients. In view of the foregoing considerations, the present research program was undertaken with the following objectives:

(a) To furnish data, obtained under carefully controlled laboratory conditions, about the in-line and transverse forces acting on smooth cylinders in an harmonically oscillating fluid at Reynolds numbers up to 1,000.000 and

(b) To identify the physical mechanism and parameters responsible for the correlation or scatter of the force-transfer coefficients.

This thesis deals only with the transverse forces acting on smooth and sand-roughened circular cylinders. It does not deal with ocean waves, non-harmonic fluid oscillations, wave and current combinations and its consequences, diffraction effects, free-surface and/or wall proximity effects, fluid elasticity or hydro-elasticity of flexible or flexibly supported cylinders in harmonic motion, or finally the interference effects between neighboring structural elements.

The transverse-force coefficient for both smooth and rough cylinders have been obtained experimentally and expressed in terms of Reynolds number, Keulegan-Carpenter number, and relative roughness. In addition, the relative frequency of vortex shedding has been determined as a function of the same parameters cited above.

II. ANALYSIS OF THE DATA AND THE FORCE COEFFICIENTS

A completely satisfactory analysis of the resistance in unsteady separated flow has escaped the concentrated efforts of many researchers. No theoretical model can, at present, predict the complete force and flow characteristics of an harmonic motion about a circular cylinder. In the absence of such an analysis, the most serious difficulty lies in the description and interpretation of the history of the flow and the effect of vortices and turbulence in the flow approaching the body at a particular time in the oscillation.

In the present study the following transverse force coefficients have been defined and evaluated:

$$CLMAX = \frac{\text{Maximum peak of the transverse force in a cycle}}{(0.5)(\rho)(D)(L)(U_m^2)} \quad (1)$$

and

$$CLRMS = \frac{\text{root-mean-square value of the transverse force in a cycle}}{0.5\rho DLU_m^2} \quad (2)$$

The frequencies of oscillation have been expressed either in terms of the frequency of oscillation of the harmonic flow as

$$f_r = \frac{\text{frequency of the first harmonic of the lift force in a cycle}}{\text{frequency of the harmonic oscillation}} \quad (3)$$

or in terms of the Strouhal number defined by

$$St = \frac{f_v D}{U_m} = \frac{f_v/f}{K} = \frac{f_r}{K} \quad (4)$$

in which ρ represents the density of fluid, D and L the diameter and length of the cylinder, U_m the amplitude of the oscillating velocity and f_v the frequency of the transverse forces.

A. GOVERNING PARAMETERS

The coefficients cited above will have to be correlated through the use of suitable parameters in order to show that they have some degree of universality within the range of the parameters encountered. A simple dimensional analysis of the flow under consideration (uniform harmonic motion about a rough circular cylinder placed with its axis normal to the flow) show that the time-dependent force coefficients may be written as:

$$\frac{F}{0.5\rho D L U_m^2} = f\left(\frac{U_m T}{D}, \frac{U_m D}{\nu}, \frac{k}{D}, \frac{t}{T}\right) \tag{5}$$

$$= f\left(K, Re, \frac{k}{D}, \frac{t}{T}\right) \tag{5a}$$

Evidently, $U_m T/D$ may be replaced by $2\pi A/D$ or simply by A/D where A represents the amplitude of the oscillations.

There is no simple way to deal with equation (5a) even for the most manageable time-dependent flows. The evaluation of the instantaneous values of the force coefficients is not at present feasible. Another and perhaps the only other alternative is to eliminate time as an independent variable in equation (5a) and consider suitable time-invariant averages or amplitudes of the force coefficients. Thus, one has

$$\left\{\begin{matrix} CLMAX \\ CLRMS \\ St \end{matrix}\right\} = f_i\left(\frac{U_m T}{D}, Re, \frac{k}{D}\right) \tag{6}$$

Equation (6), in spite of its simplicity, gives rise to many questions: Do the averaged force coefficients really depend upon both Re and K; Are K and Re the most suitable governing parameters; Can one obtain meaningful conclusions by plotting the data for a given coefficient with respect to, say, K and connecting points having equal Re or vice versa; How should the experiments be conducted so that equation (6) yields manageable plots; Which of the two parameters has a more pronounced effect on the force coefficient under consideration; Why has there been considerable scatter in the field data when plotted with respect to either K or Re; Are there ranges of K and Re in which the effect of one is obscured by a reasonable correlation of the force coefficients with the other? These and similar questions have been raised by many other investigators and attempts were made to establish suitable correlations. The state of the art is such that the past conclusions and conjectures can be critically scrutinized only through the acquisition of data of high intrinsic quality obtained under controlled laboratory conditions with relatively simple harmonic flow situations. The purpose of such an effort is by no means to remove the need for actual full scale experience, in fact it is to encourage full scale experiments and to enable those concerned to interpret and better understand the factors affecting the force-transfer function.

Past experience [9,5] has shown that the force coefficients obtained under controlled laboratory conditions are primarily functions of K at relatively small Reynolds numbers (Re < 25,000) and that the effect of viscosity is obscured by the fairly good correlation between K and the force coefficients. Again previous efforts and the reasoning based on dimensional analysis have shown that there is an undeniable effect of

the Reynolds number. Thus, means have to be devised to delineate the effect of both K and Re or some other viscosity dependent parameter [8].

It is apparent that the maximum velocity U_m appears in both $K = U_m T/D$ and $Re = U_m D/\nu$. Simple rules of dimensional analysis state that one obtains the maximum amount of experimental control over the dimensionless variables, if the original variables, that can be regulated, each occur in only one dimensionless product. Thus, if U_m is easily varied experimentally, then U_m should occur in only one of the independent dimensionless parameters. With this hint in mind, Re in equation (6) is replaced by $Re/K = D^2/\nu T$. This parameter shall be called the -frequency parameter- and denoted by β, so that

$$\beta = D^2/\nu T \tag{7}$$

Evidently, for a series of experiments conducted with a cylinder of a given diameter in water (of uniform and constant temperature and density) undergoing harmonic oscillations with a constant period (T), β is held constant. Then the variation of a force coefficient with K may be plotted for constant values of β. Subsequently, one can easily recover the Reynolds number from

$$Re = \beta K \tag{8}$$

and connect the points, on each β = constant curve, representing a given Reynolds number for a family of suitably selected values of the Reynolds number. Such a procedure eliminates the difficulty of trying to draw contours of constant K, or constant Re, or constant CLMAX or CLRMS versus K or Re or K versus Re. Suffice it to note that the data reported here-in

shall be analyzed according to the relationship

$$C_i = f_i(K, \beta, \frac{k}{D}) \tag{9}$$

[a coefficient]

and the Reynolds number will be used in the manner cited above. The power of this new plotting procedure (new, as far as the wave force analysis is concerned) will become apparent later.

III. EXPERIMENTAL EQUIPMENT AND PROCEDURES

A. U-SHAPED OSCILLATING-FLOW TUNNEL

Experiments carried out by Sarpkaya and Tuter [5] in the initial phases of the study with small smooth cylinders at relatively low Reynolds numbers have proved the versatility and the usefulness of a U-shaped oscillating-flow apparatus. Thus, in an attempt to achieve larger Reynolds numbers, it was only natural to construct a larger U-shaped tunnel.

Among the various designs, the one shown in figure 1 was finally selected for construction [8]. A photograph of the completed and fully instrumented structure is shown in figure 2. It consists of eleven modules for ease of construction, transportation, and mounting. Each module is made of 0.95 cm. (3/8 inch) aluminum plates and reinforced with 1.27 x 10 x 46 cm. (1/2 x 4 x 18 inches) aluminum flanges welded to the plates. The modules were assembled with the help of an air drying silicon rubber seal between the flanges of two adjacent modules and 2.54 cm. (1 inch) steel bolts placed 15 cm. (6 inches) apart. The inside of each module was precision machined so that the largest misalignment was about 1 mm. (0.04 inches).

Prior to the description of its instrumentation and operation, a few words are necessary about the general shape of the tunnel. The cross-section of the two legs is 183 x 91.5 cm. (6 x 3 feet). This selection was dictated by several considerations such as available ceiling height, pressures to be encountered and hence the structural and

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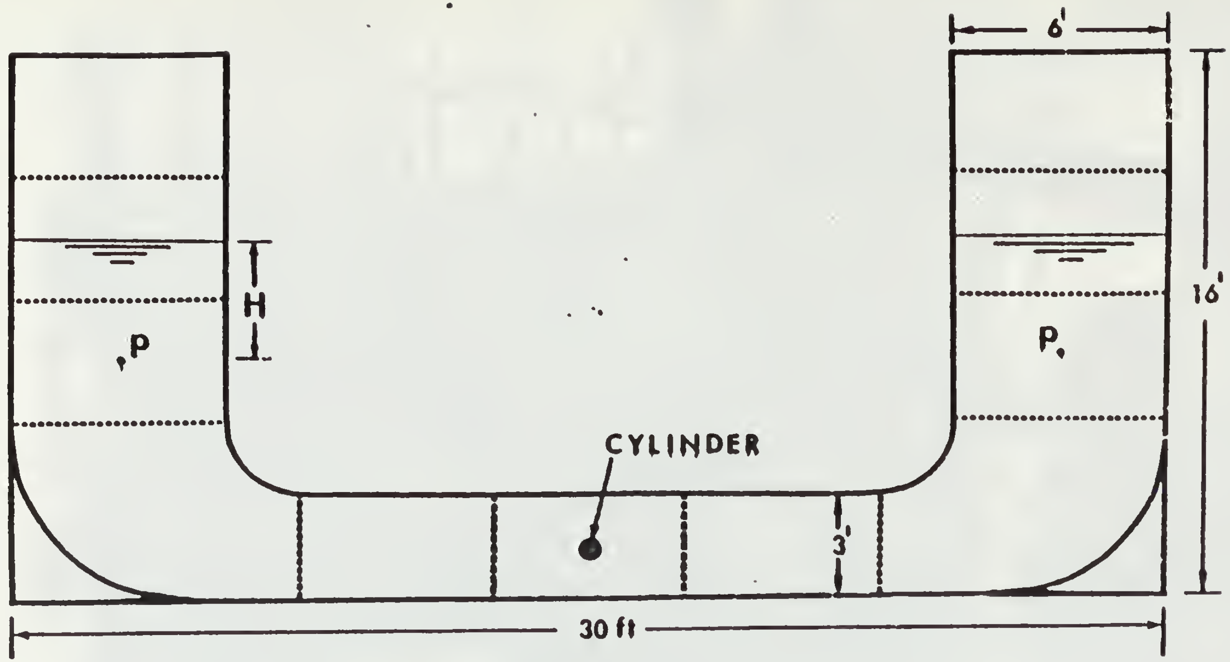

Fig. 1 Schematic drawing of the U-shaped vertical water tunnel.

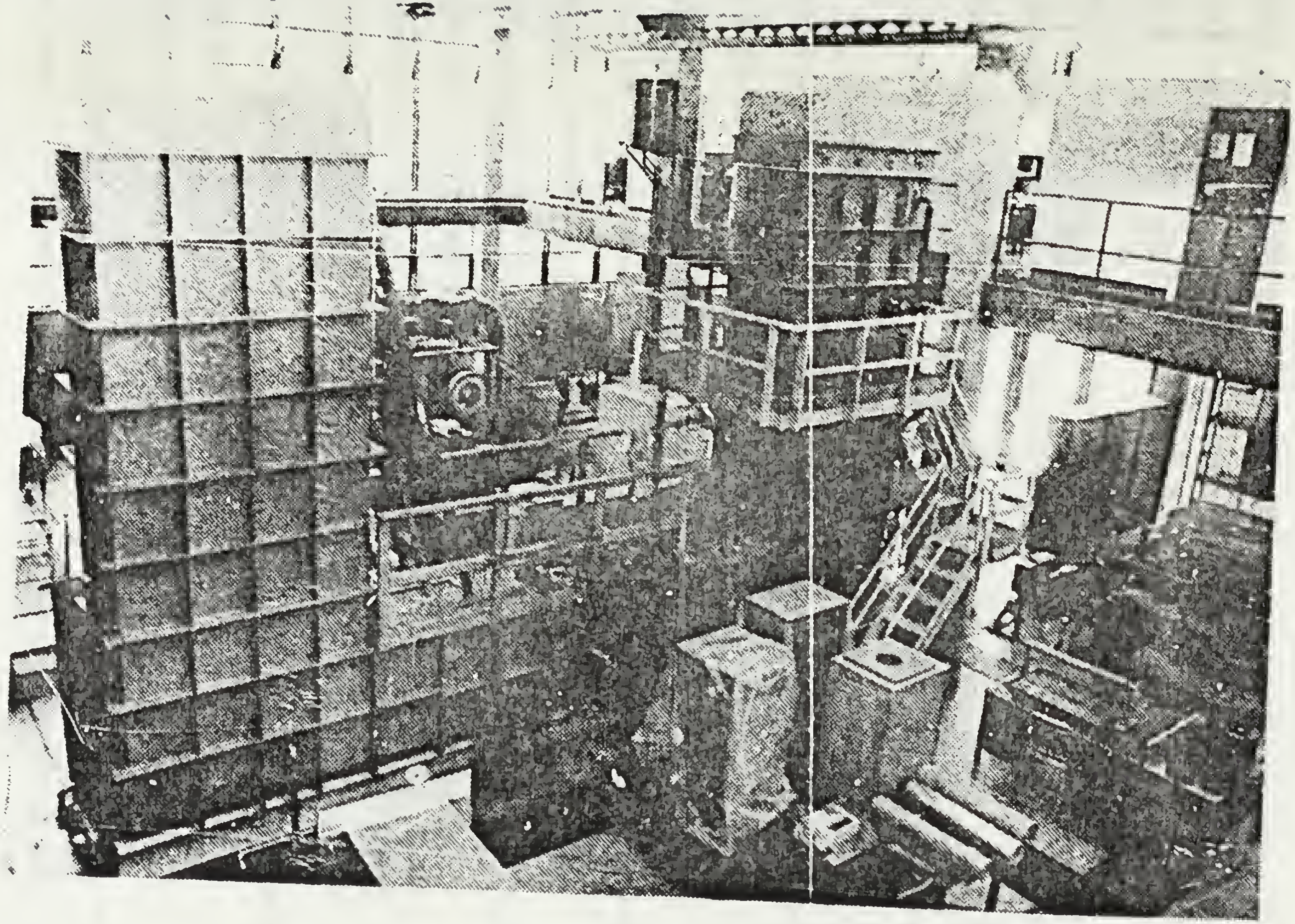

Figure 2. Photograph of the U-Tunnel

economic considerations, desire to obtain a virtual amplitude* or velocity of oscillation at least twice that of the free surface, period of oscillation, Reynolds number and the relative amplitude A/D desired, natural-damping of the oscillations, and the magnitude and the frequency of the forces. The length of the horizontal test section was chosen larger than twice the virtual amplitude to insure fully developed uniform flow at the test section. Finally the two corners of the tunnel were carefully streamlined to prevent flow separation (see figure 1). This design proved to be more than adequate for no separation was encountered, and also the desired frequency and amplitude of oscillation were achieved.

The auxiliary components of the tunnel consisted of plumbing for the filling and emptying of the tunnel with hot and cold water, a heat exchanger, butterfly-valve system, and the air supply system. The plumbing consisted of simple piping, valves, a small pump, and a filter. None of these will be described further.

The butterfly-valve system (mounted on top of one of the legs of the tunnel) consisted of four plates, each 4.6 cm. (18 inches) wide and 92 cm. (36 inches) long. A 2.54 cm. (1 inch) steel shaft was placed at the axis of each valve plate.(see figure 3). Aluminum housings supported both ends of the shaft with self-aligning ball bearings. A 15 cm. (6 inches) gear was attached to one end of each shaft which extended beyond the bearing. All four valve plates were then aligned and

*The virtual amplitude is defined as the amplitude of oscillation which the cylinder experiences. Here it is exactly twice the amplitude of oscillation of the free surface in one leg of the tunnel.

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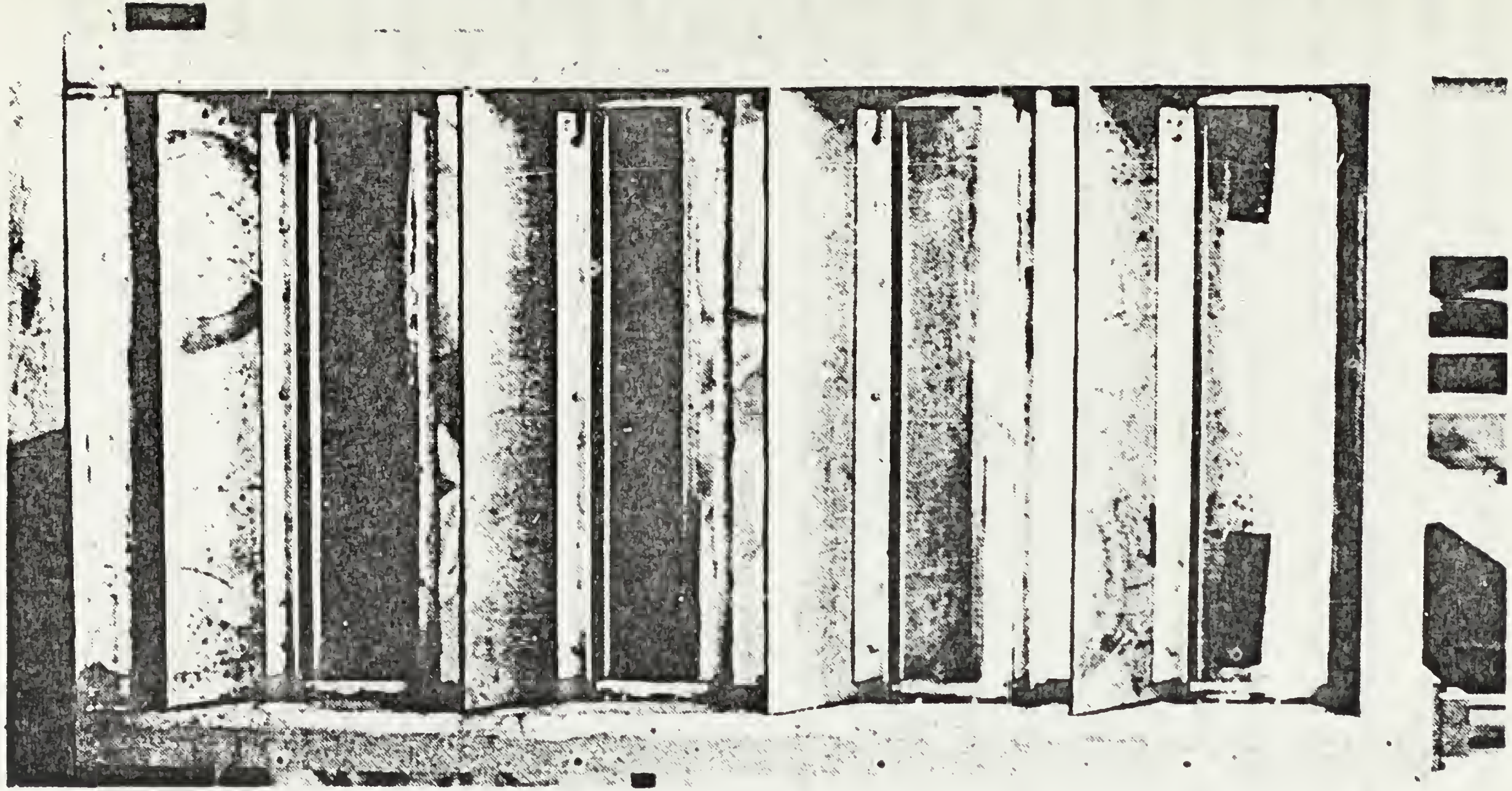

Figure 3. Photograph of butterfly valve system

driven by a simple rack and pinion system. The rack was actuated by an air-driven piston with the help of a three-way valve connected to the laboratory air supply system.

The valves, in their closed position, completely sealed the top of one of the legs of the tunnel. The top of the other leg was left open. Initially, the butterfly valves were closed and air was admitted to that side of the tunnel to create the desired differential water level between the two legs of the tunnel. Then the valves were opened quickly with the help of a pneumatically-driven three-way control valve. This action set the fluid in the tunnel in oscillatory motion with a natural period of T = 5.507 seconds. A series of experiments was conducted with one of the test cylinders to evaluate some of the experimental characteristics of the tunnel. It was found that the damping of the motion is such that the amplitude of oscillations decreases about 3 mm. (0.12 inches) per cycle and about 0.15 mm.(0.06 inches) per cycle for amplitudes half or less than of the maximum. Thus, over a period of four or five complete cycles of oscillation at any amplitude, the amplitude, velocity, and the acceleration of the fluid changed about one percent. Evidently the forced oscillations of the fluid, if such a method were to be employed, cannot yield the amplitude to an accuracy better than one percent. Additionally in such a method one has to contend with some high frequency vibrations, however small, superimposed on the acceleration. These result from the cyclic operation of the butterfly valves. It is because of these considerations that the experiments were carried out by letting the system damp out the amplitude over many cycles of oscillations. The advantages of the method adopted become apparent very quickly. Firstly, the oscillations were so smooth and quiet that one could not know or

even hear that 5000 gallons of water were in oscillation. The elevation, acceleration, and all force traces were absolutely free from secondary oscillations so that no filters whatsoever were used between the transducer output and the recording equipment. Secondly, the method adopted enables one to cover all possible values of K for a given β and k/D and see the evolution of the forces over a period of about 30 minutes.

B. CIRCULAR CYLINDER MODELS

Circular cylinders with diameters ranging in size from 20.3 cm. (8 inches) to 5 cm. (2 inches) have been used in this study. The cylinders were turned on a lathe from aluminum pipes or plexiglass rods and polished to a mirror-shine surface. There is no doubt that the surfaces were hydrodynamically smooth. The length of each cylinder was such that it allowed 0.08 cm. (1/32 inch) gap between the tunnel wall and each end of the cylinder. As will be noted later, the cylinder was prevented from moving towards one or the other wall by means of small O-rings attached to the round cantilever end of the force transducers. A double-ball precision bearing (SKF-2303-J) with an approximately 1.5 cm. (0.6 inches) bore was inserted at each end of the cylinder in aluminum housings which sealed the cylinder air tight. The other face of each bearing was flush with the end of the cylinder. The same cylinders were also used as rough cylinders by coating them with sand of desired size. For this purpose clean sand was screened through the use of the combination of appropriate size sieves to separate the desired size. The cylinder surface was then cleaned with alcohol and carefully coated with an epoxy paint. After considerable practice of application of the epoxy paint it has been possible to obtain an extremely thin and uniform coating

which was free of ridges, waves and local buildup. Next, the selected sand was sprinkled over the gently-rotating cylinder with a sieve slightly larger than the sand particles. The excess sand was easily removed after about 15 minutes through gentle rubbing by hand. The resulting roughness was perfect beyond expectation as evidenced by the two sample photographs shown in figure 4. The pictures of the rough surface were taken with a scanning electron miscroscope. The actual size of the sample sand is shown in the figure.

It was necessary to choose the proper size of the sand for each cylinder in order to maintain the k/D ratios ($k/D \sim 1/195$ and $k/D \sim 1/370$), besides the smooth cylinder, selected. Furthermore, it was necessary to carry out the experiments for a given cylinder at various temperatures in order to vary $D^2/\nu T$ or, in other words, to investigate the variation of the lift coefficient with Reynolds number for a given Keulegan-Carpenter number and relative roughness. The water in the tunnel was heated to the desired temperature through the use of the heat exchanger cited previously. The temperature in the tunnel remained constant for a period of several hours thus, it was not necessary to continuously circulate the water through the heat exchanger. Evidently, the enormous heat capacity of the tunnel and the fluid helped to maintain a constant and uniform temperature. The expansion of the test cylinders was less than 1/32 inches (0.8 mm) at the highest temperature tested.

C. FORCE MEASUREMENTS

Two identical force transducers, one at each end of the cylinder, were used to measure the instantaneous in-line and transverse forces.

k = 0.018"
20-X

k = 0.018"
50-X

Figure 4. Scanning Electron Microscope Photographs of sand-roughened surface

The basic transducer was manufactured by B.L.H. Electronics, Inc. under the trade name LBP-1 and catalogue no. 420271. A photograph of the gage assembly is shown in figure 5. The gage had a capacity of 2224 N (500 lbf.) with an overload capacity of 200 percent. The deflection of the gage under 500 lbf. load was 0.25 mm. (0.01 inch). For the largest cylinder and amplitude encountered in the experiments, the maximum load was less than 200 lbf., and the deflection of the beam was less than 0.2 mm. (0.008 inches).

A special housing was built for each gage so that it can be mounted on the tunnel window and rotated to measure either the in-line or the transverse force alone. The bellows which protected the strain gages had to be waterproofed in such a manner that they would not adversely effect the operation of the gages when subjected to about 6 m. (20 feet) water pressure at temperatures 18 C (64 F) to 74 C (165 F). For this purpose the bellows were completely filled with Dow Corning 3140—RTV coating without bringing the rubber into contact with air during the filling operation. After filling, the ends of the bellows were sealed air tight with special clamps. The silicon rubber remained in its original liquid form throughout the operation of the gages.

The cylinders were placed in the test section by retracting the gages from their housing and then pushing them into the bearings mounted on each end of the cylinders. As noted earlier the O-rings placed on the cantilever end of each gage prevented the test cylinders from moving sideways towards one or the other wall and helped to exactly set the 0.8 mm. (1/32 inch) space between the cylinders and the tunnel wall. The cylinders were free to rotate at the application of a slight torque by hand.

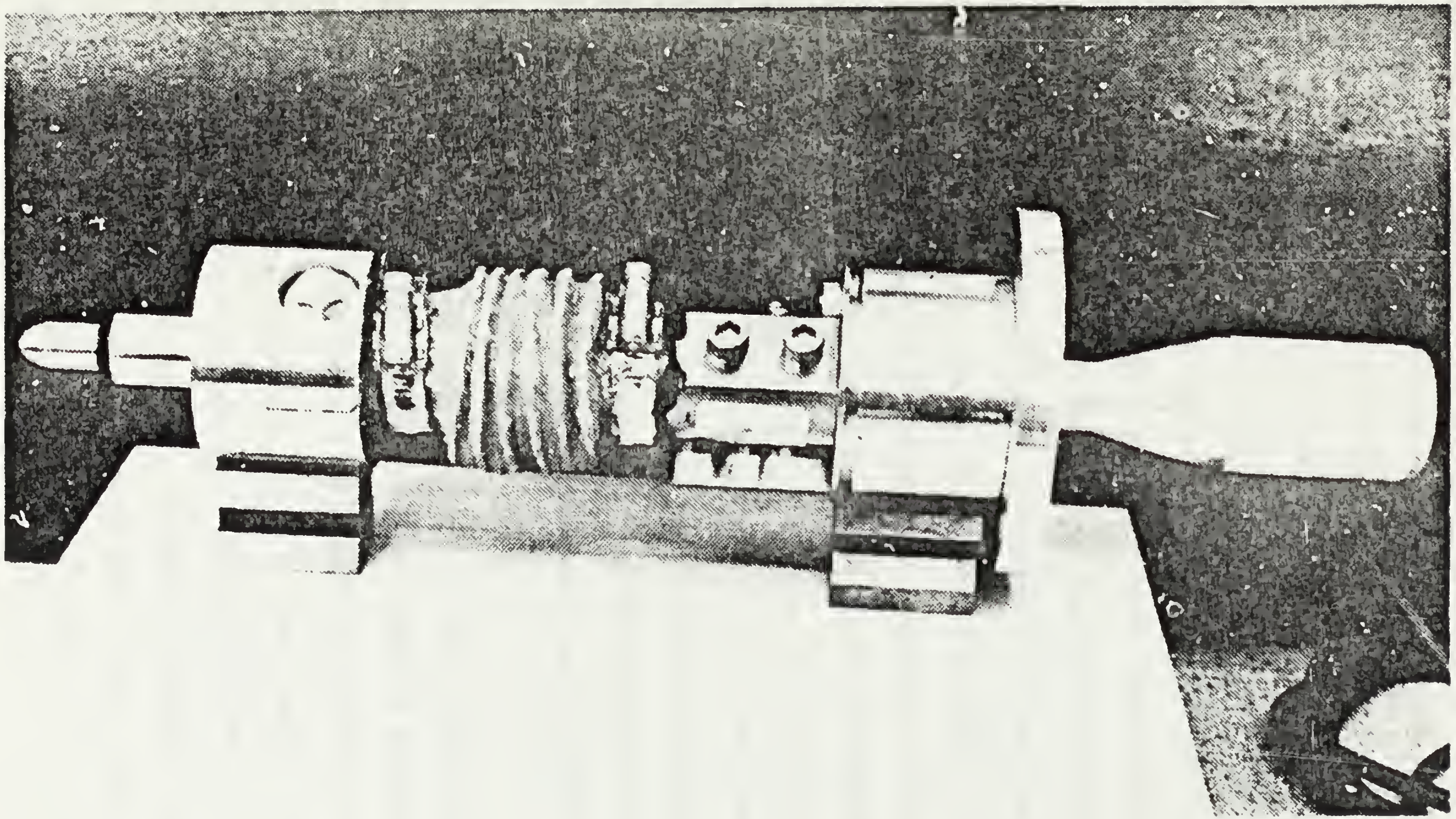

Figure 5. Gage Assembly

After the mounting of the first cylinder, the exact angular position of the gages within their housing had to be determined and set with a pin so that the gages measure either only the in-line or the transverse force. For this purpose, an approximately 400 N load was hung on the cylinder with a lubricated nylon rope. The in-line force (acting in the horizontal direction) was observed on the amplifier recorder system. Then the gage was rotated in small increments until the in-line force was exactly zero. A final check was made by measuring the outputs of the gages with a precision voltmeter. The position of each gage was marked and set with a pin. Finally, four bolts were placed on the gage housing to hold the gages rigidly in position. Removal of these bolts and the pin allowed the rotation of the gages exactly 90 degrees, after which the bolts and pin were placed in position. In this manner the gages were capable of measuring either the in-line or the transverse force without any "cross talk" between the in-line and transverse forces. Ordinarily, one gage was set to measure in-line force and the other gage the transverse force. At times both gages were used to measure only the in-line or the transverse force.

The calibration of each gage was accomplished by hanging loads in the middle of the cylinder after setting both gages to sense only the transverse (here vertical) force. The directional sensitivity of the gages was also checked by applying identical loads upwards on the test cylinders with the help of a hook-cantilever arm attached to the top of the tunnel outside the test section. Repeated calibrations have shown that the gages are perfectly linear up to 2000 N; they yield the same signal for loads applied either downward or upwards; and that the gages,

together with the electronic system to which they were eventually connected were capable of sensing forces as small as 0.1 N (0.02 lbf.).

The in-line and transverse force were simultaneously recorded with the instantaneous acceleration on two two-channel Honeywell recorders running at a speed of 10 divisions per second. This speed gave 55.07 divisions per cycle. The amplitude of the transverse force and the flow characteristics such as $U_m T/D$ and Re were determined from these traces. RMS value of the lift force was determined for each cycle by reading the force at every division or 0.1 second intervals. Sample transverse force and elevation traces are shown in figure 6.

D. ACCELERATION, ELEVATION, OR VELOCITY MEASUREMENTS

It is because of the extreme importance of the accurate measurement of the instantaneous value of these quantities that they are discussed here separately.

Firstly, it should be noted that the measurement of the amplitude, acceleration, elevation, or the velocity is a matter of interpretation of the signal received from the appropriate transducer in light of one of the following expressions

$$U_m = \frac{2\pi A}{T}, \quad a_m = \frac{dU}{dt} = (\frac{2\pi}{T})^2 A = \frac{2\pi}{T} U_m$$

in which T = 5.507 seconds for the experiments reported here.

Three transducers were used to generate three independent d.c. signals, each proportional to the instantaneous value of one of the quantities cited above. The first one consisted of a seven foot long platinum wire stretched vertically in one leg of the tunnel. The output of the capacitance-wire bridge was connected to an eight channel

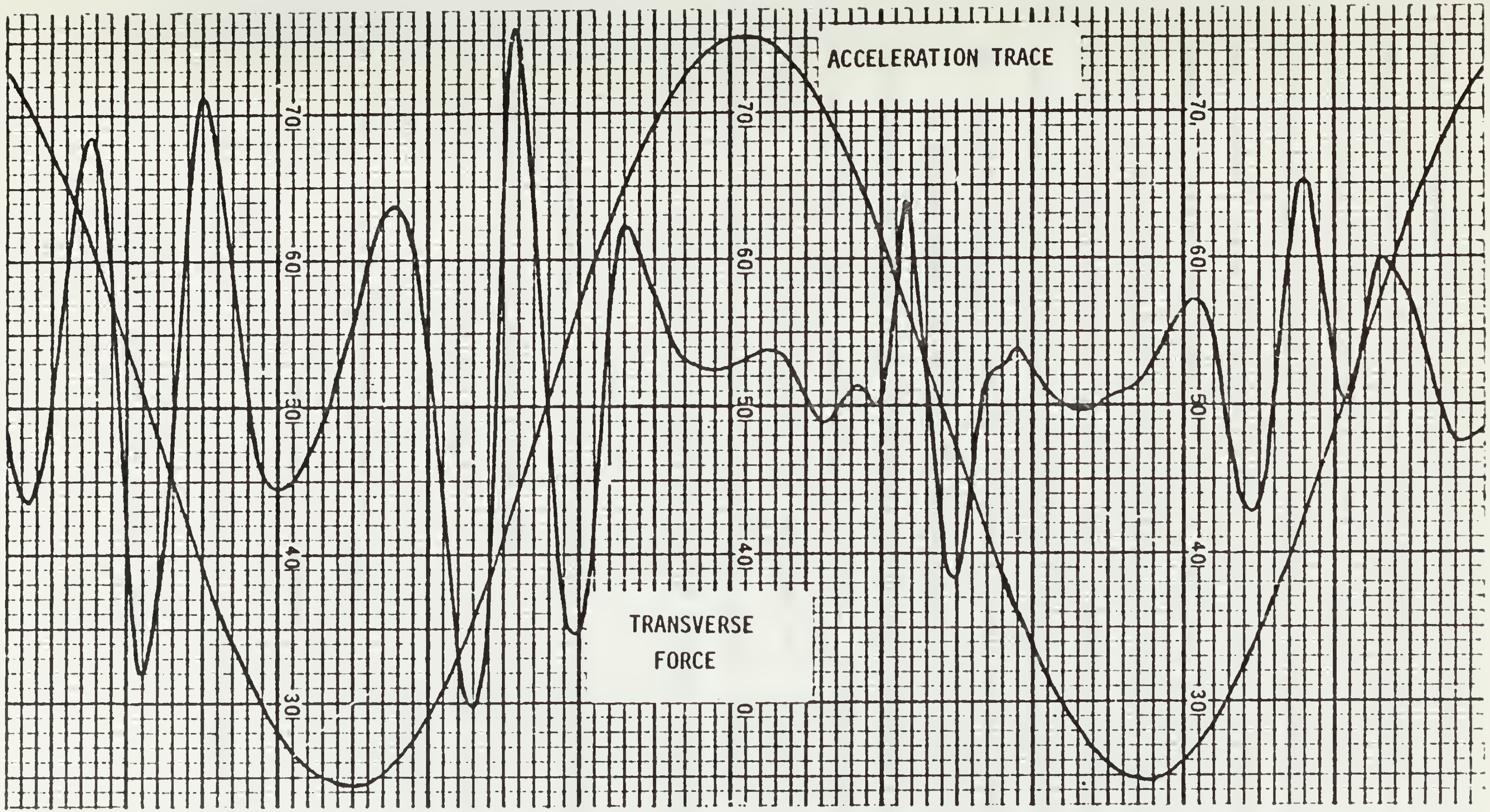

Figure 6. Acceleration and transverse force traces

amplifier-recorder system. The response of the wire was found to be perfectly linear within the range of oscillations encountered. The wire was capable of yielding a measurable signal for changes in water elevation as small as 0.8 mm. (1/32 inches). Such a sensitivity was not, however, always desirable for the instabilities on the water surface gave rise to small oscillations in the analog records. The effect of such instabilities were practically eliminated by placing the wire along the axis of 30 cm. (1 foot) diameter and 213 cm. (7 feet) long thin plastic pipe. Be that as it may, the use of this wire was rendered unnecessary due to the use of a more reliable method.

The second method consisted of the measurement of the instantaneous acceleration by means of a differential-pressure transducer connected to two pressure taps placed horizontally 61 cm. (2 feet) apart and 91.5 cm. (3 feet) to one side of the test section. The output of the transducer was again connected to the eight channel recorder. The instantaneous acceleration was then calculated from $\Delta p = \rho s(dU/dt)$ where

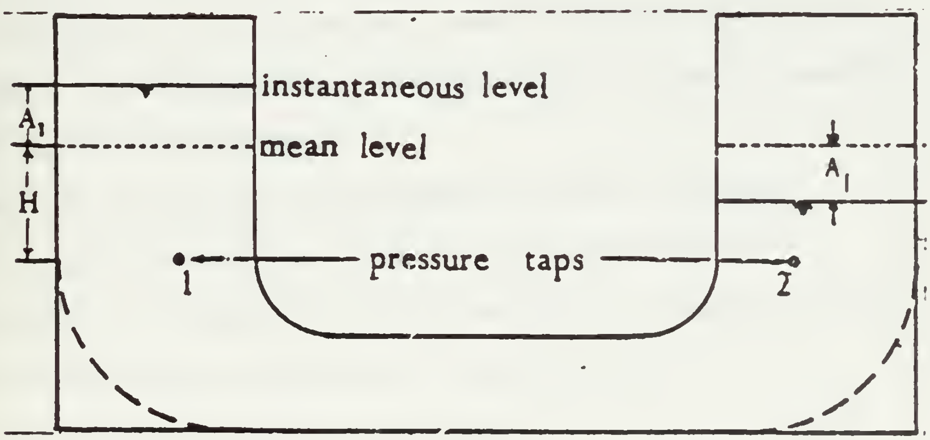

Figure 7. Position of pressure taps

Δp is the differential pressure, s the distance between the pressure taps and dU/dt is the instantaneous acceleration of the fluid. The effect of the pressure drop due to the viscous forces over the distance s was calculated to be negligible.

The third method again consisted of the measurement of the differential pressure between two pressure taps. The two taps were placed symmetrically on the two vertical legs of the tunnel at an elevation 127.0 cm. (50 inches), (see figure 7) below the mean water level, i.e., H = 38 in. Applying Bernoulli's equation for unsteady flow between each pressure tap and the instantaneous level of water, it is easy to show that twice the amplitude of the free surface oscillation (virtual amplitude) is given by

$$A = 2A_1 = \frac{\Delta p/\gamma}{1 - \frac{1}{g}\left(\frac{2\pi}{T}\right)^2 H} \qquad (10)$$

in which g and T are constant and H is kept constant. Thus the signal of this transducer yielded the virtual amplitude or the maximum velocity in each cycle. It was entirely free from noise or small free surface effect. The transducer was calibrated and its linearity checked before each series of experiments.

Suffice it to say that all three methods gave nearly identical results and yielded the amplitude, velocity, or acceleration to an accuracy of about two percent relative to each other. These comparisons as well as the perfectly sinusoidal and noise-free character of all pressure and force traces speak for the suitability of the unique test facility used in this study.

E. DATA REDUCTION

Experiments were repeated at least three times for each cylinder. Often only two, but at times as many as four runs were evaluated. Suitably selected cyles were read every 0.1 second and the tabulated data were transferred to the computer data cards together with additional relevant information such as calibration factors, cylinder diameters, number of data cards, etc. A computer program calculated the force transfer coefficients previously discussed (see Appendix A).

It should be emphasized once again that only the amplitude and frequency of the first harmonic of the transverse forces were evaluated. Ordinarily one would write the transverse force as

$$F(t) = \sum_{n=1}^{\infty} \left[a_n \sin\left(\frac{2\pi n t}{T}\right) + b_n \cos\left(\frac{2\pi n t}{T}\right)\right] \tag{11}$$

and attempt to evaluate the coefficients a_n and b_n or the coefficients a_n and the phase angle for each harmonic. In view of the fact that this is a highly time consuming affair and that the first harmonic is almost always several times larger than the second or higher harmonics, it was decided to evaluate only the characteristics of the first harmonic. This together with the RMS values of the transverse force gives sufficient information about the characteristics of the transverse force.

IV. DISCUSSION OF RESULTS

A. BLOCKAGE AND LENGTH-TO-DIAMETER EFFECTS

Attempts to achieve as high Reynolds numbers as possible in conducting wind-tunnel or water-tunnel experiments invariably give rise to wall-interference effects which, of course, influence whatever measurements are desired. There are several blockage correction formulas for steady flows which might be used so that the wall-interference effects might be minimized. Unfortunately none of these formulas could be used in the present study for no one has demonstrated that the blockage effects in oscillatory flow are identical to those experienced in steady flows.

The blockage ratio D/w, where D is the diameter of the cylinder and w the width or height of the test section, and the length- or span-to-diameter ratio, L/D, for the cylinders used in the present study are tabulated below [w = 91.44 cm. (3 feet), L = 90.885 cm. (2.9818 feet)].

D	D/w	L/D
20.244 cm. (7.970 inches)	0.22	4.49
16.447 cm. (6.475 inches)	0.18	5.52
15.177 cm. (5.975 inches)	0.17	5.99
12.674 cm. (4.990 inches)	0.14	7.17
10.103 cm. (3.978 inches)	0.11	8.99
7.544 cm. (2.970 inches)	0.082	12.05
6.349 cm. (2.4996 inches)	0.069	14.31
5.057 cm. (1.991 inches)	0.055	17.97

Achenbach (10) and in some of the experiments of Fage and Falkner (11) the blockage ratios were 0.166 and 0.185 respectively. The length-to-diameter ratio in Fage and Warsap's (12) experiments was 20.2 or 7.88, depending on the diameter of the two cylinders they used, as compared to 3.33 in the experiments of Achenbach. Evidently, the formulas used for steady flow correction effects cannot be applied to oscillating flows and that there is not a unique blockage correction for the entire period of the harmonic flow. This is evident from the fact that within a given cycle the fluid undergoes varying accelerations and velocities as the wake width, momentum deficiency, and the wake pressure change accordingly. Thus, a blockage correction made for the instant of maximum velocity is not applicable to the instant at which the maximum acceleration occurs. In view of the fact that there are no previous investigations, a series of experiments had to be conducted to determine the role of blockage in the flow under consideration. For this purpose a differential pressure transducer was connected to two pressure taps on the same side of the tunnel wall. One of the taps was placed on the wall directly above the axis of the test cylinder. The other tap was placed 76 cm. (29.92 inches) to one side of the first tap along a line parallel to the flow. A series of experiments were carried out with the 16.447 cm. (6.475 inches) cylinder and the differential pressure was recorded and compared with the differential pressure obtained from the acceleration transducer. Furthermore, to simplify the comparison both transducers were calibrated so as to render exactly the same output under identical calibration loads. The results have shown that the two differential pressures were nearly identical and that they were certainly

within three percent of each other. Often the two traces of two transducers were indistinguishably coincident. This somewhat surprising result is a clear indication of the fact that the blockage effect in harmonic flows is negligible at least for D/w ratios less than about 0.20. Although no special attempt was made to interpret the lack of blockage effect in such flows it is believed that the presence of vortices on both sides of the cylinder together with the high periods of acceleration and velocity render the flow relatively more uniform at short distances away from the cylinder in the test section. Therefore, for the reasons cited above no blockage-effect corrections were applied to the data presented here. It might be of interest to note that had the flow been assumed uniform and had the maximum velocity for the largest cylinder and the Reynolds number were used to calculate a blockage effect correction through the use of one of the existing formulas, one would have found that such a correction would have amounted to about six percent.

B. TRANSVERSE FORCE DATA

1. Smooth Cylinder

The transverse force coefficients for smooth cylinders are plotted as a function of K in figures 8 through 14. These data are also tabulated and presented in Appendix B. It is evident from these figures that CLMAX shows some scatter which is in fact smaller than one would have anticipated in view of the complex texture of the transverse force. It is also evident that CLMAX begins to rise rapidly from K ≈ 6 to 12 and then decreases as K increases. As noted earlier the Reynolds number along each plot varies with K and β. One can designate special values of the Reynolds number along this curve simply by writing Re = Kβ or by finding the K values which correspond to a particular value of Re

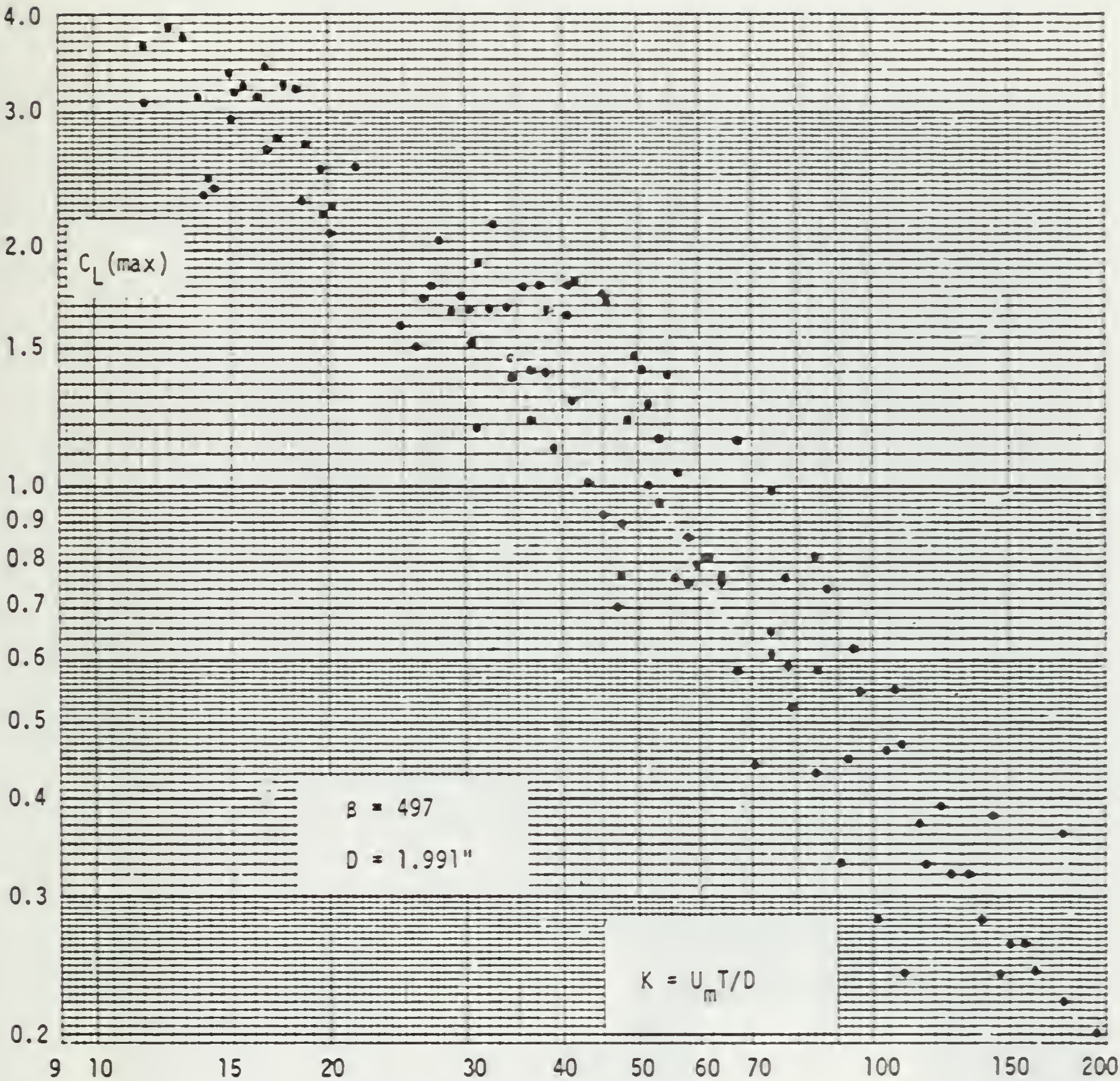

Fig. 8 C_L(max) versus K for β = 497.

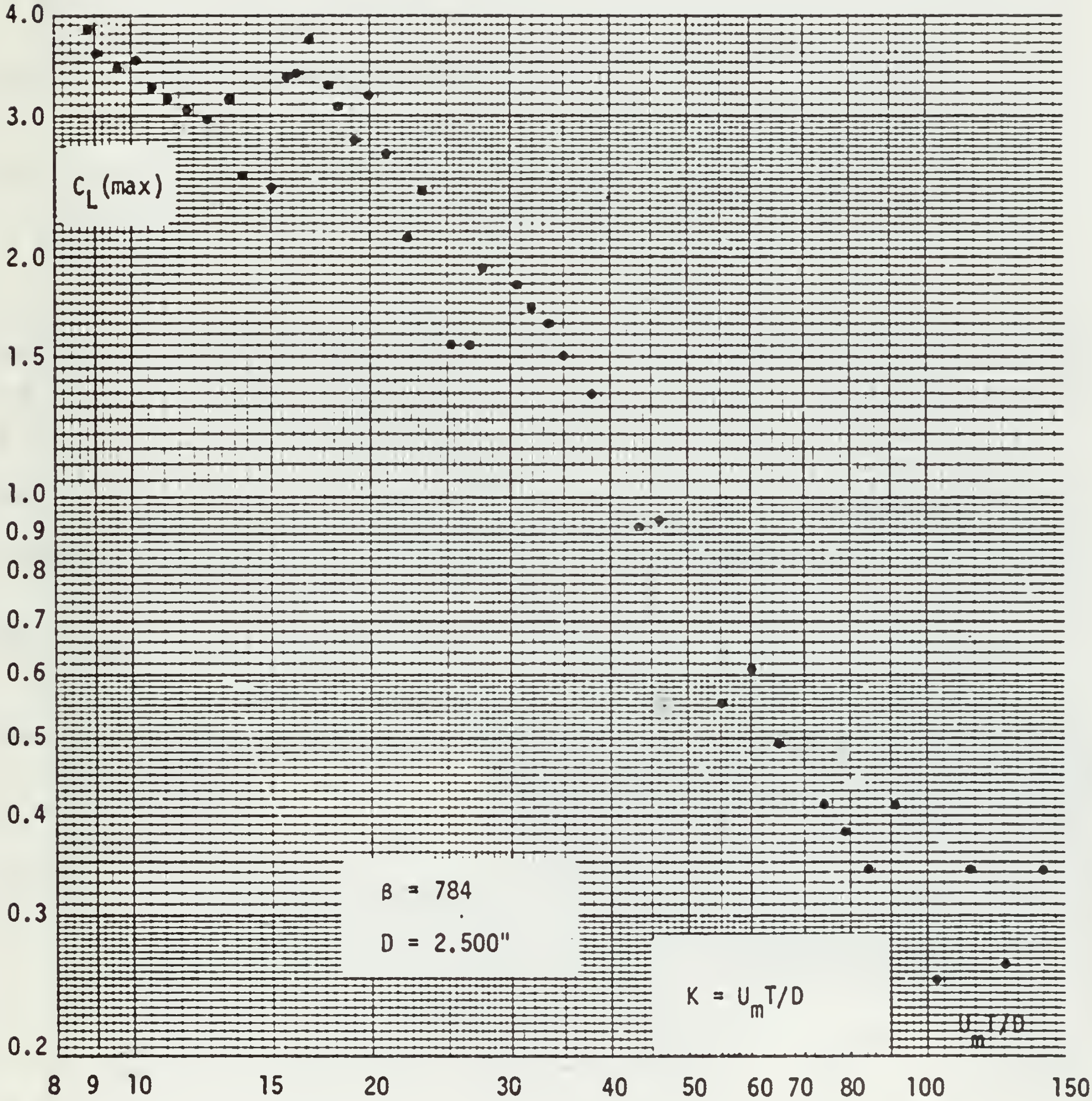

Fig. 9 C_L(max) versus K for β = 784.

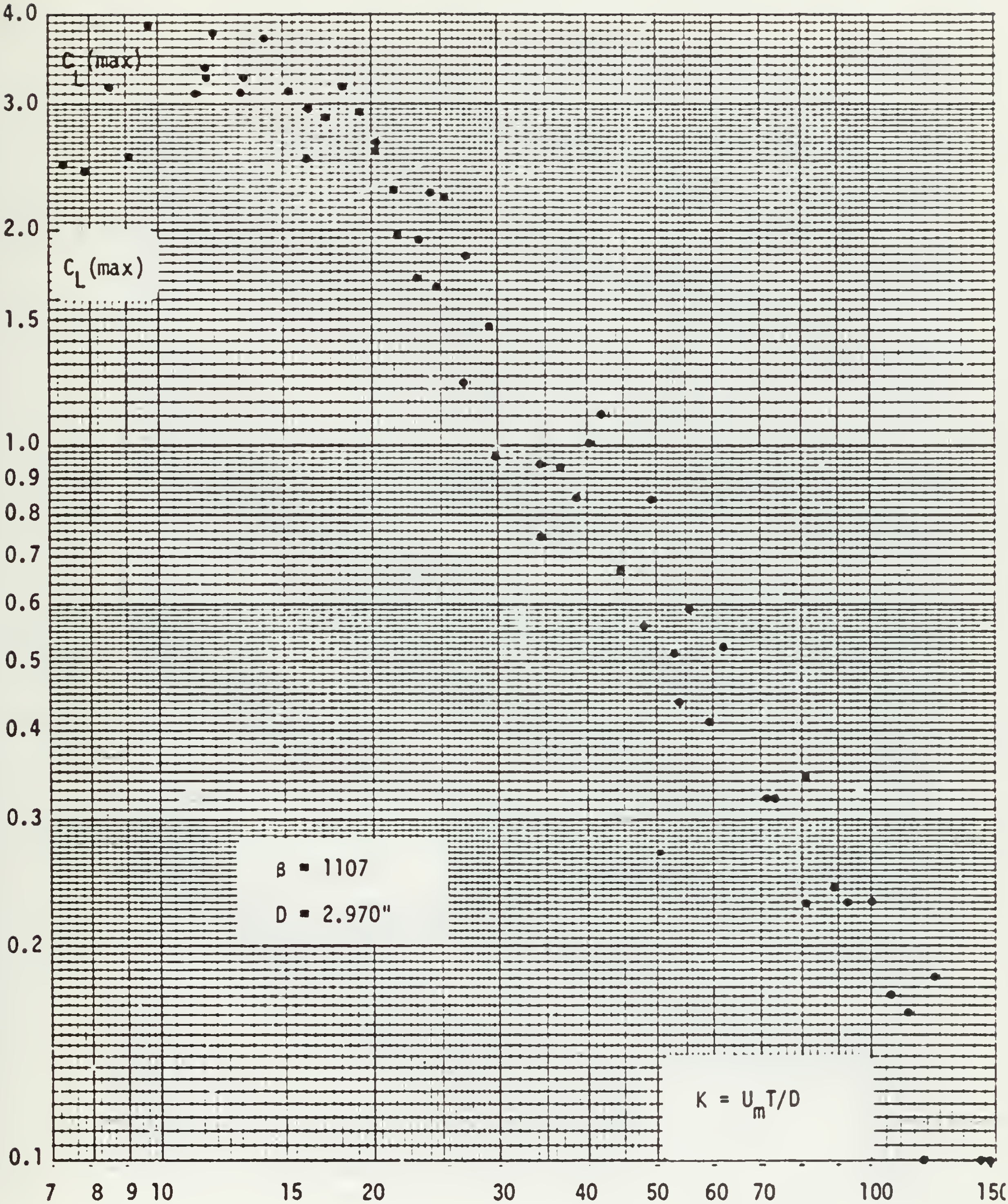

Fig. 10 C_L(max) versus K for β = 1107.

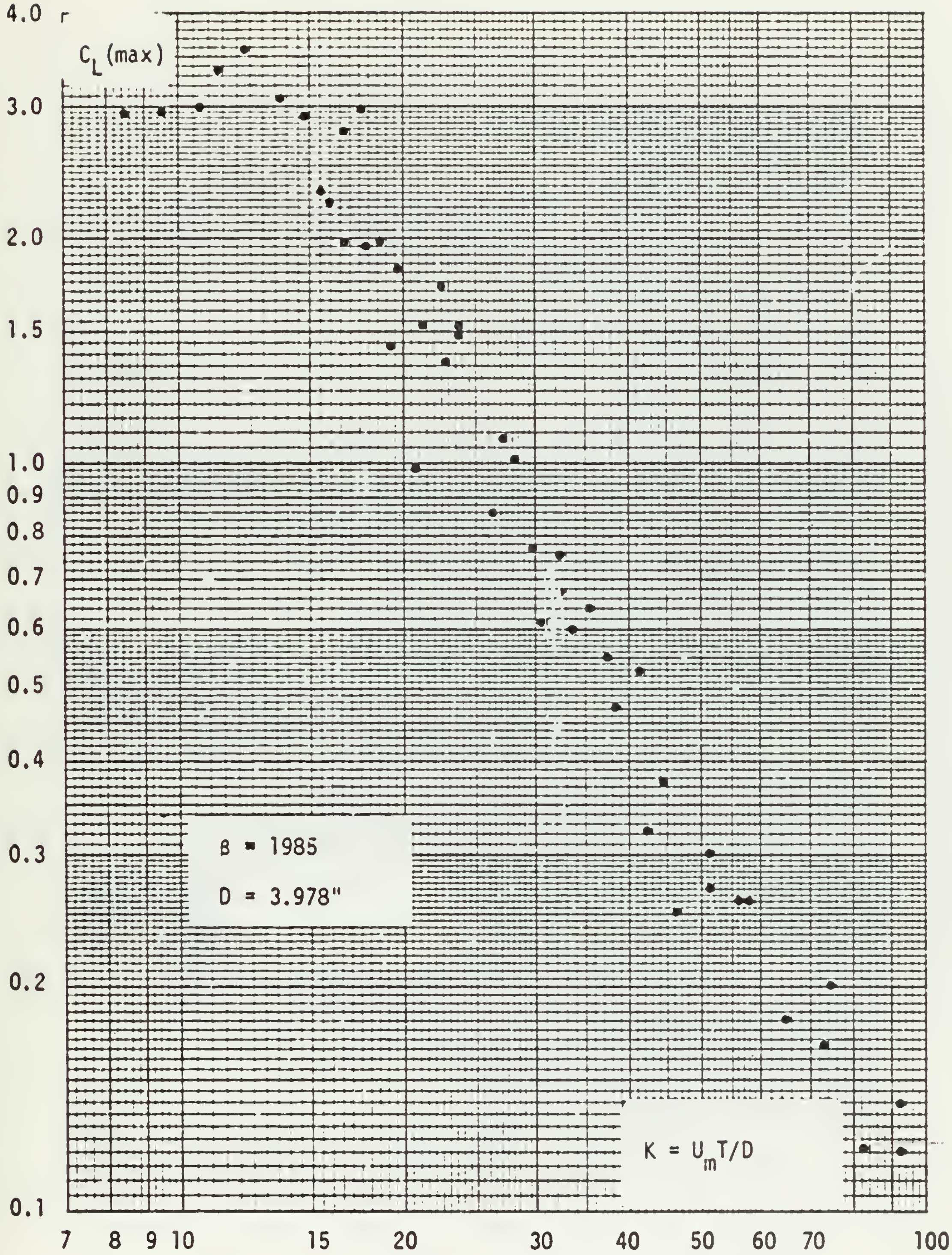

Fig. 11 C_L(max) versus K for β = 1985.

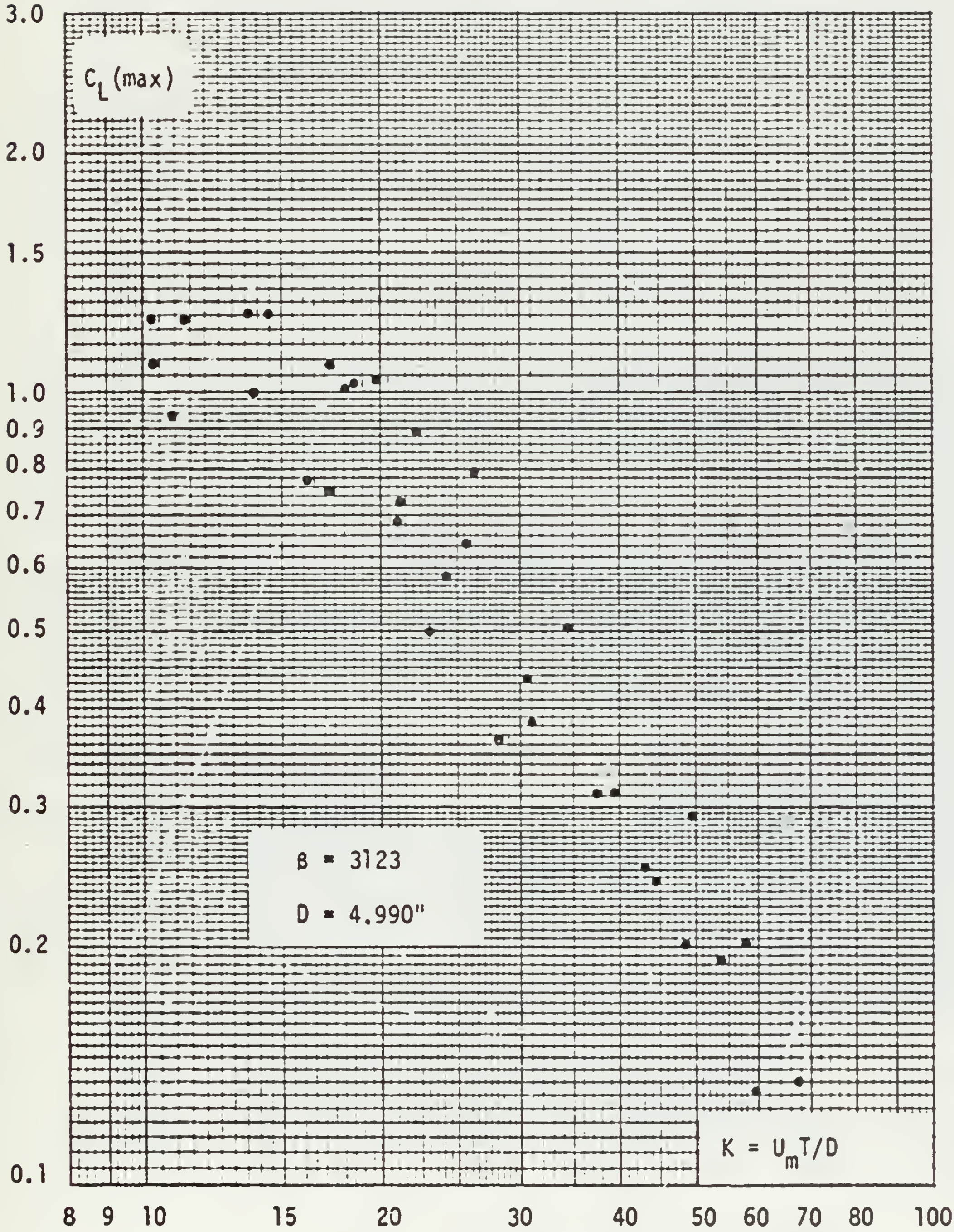

Fig. 12 C_L(max) versus K for β = 3123.

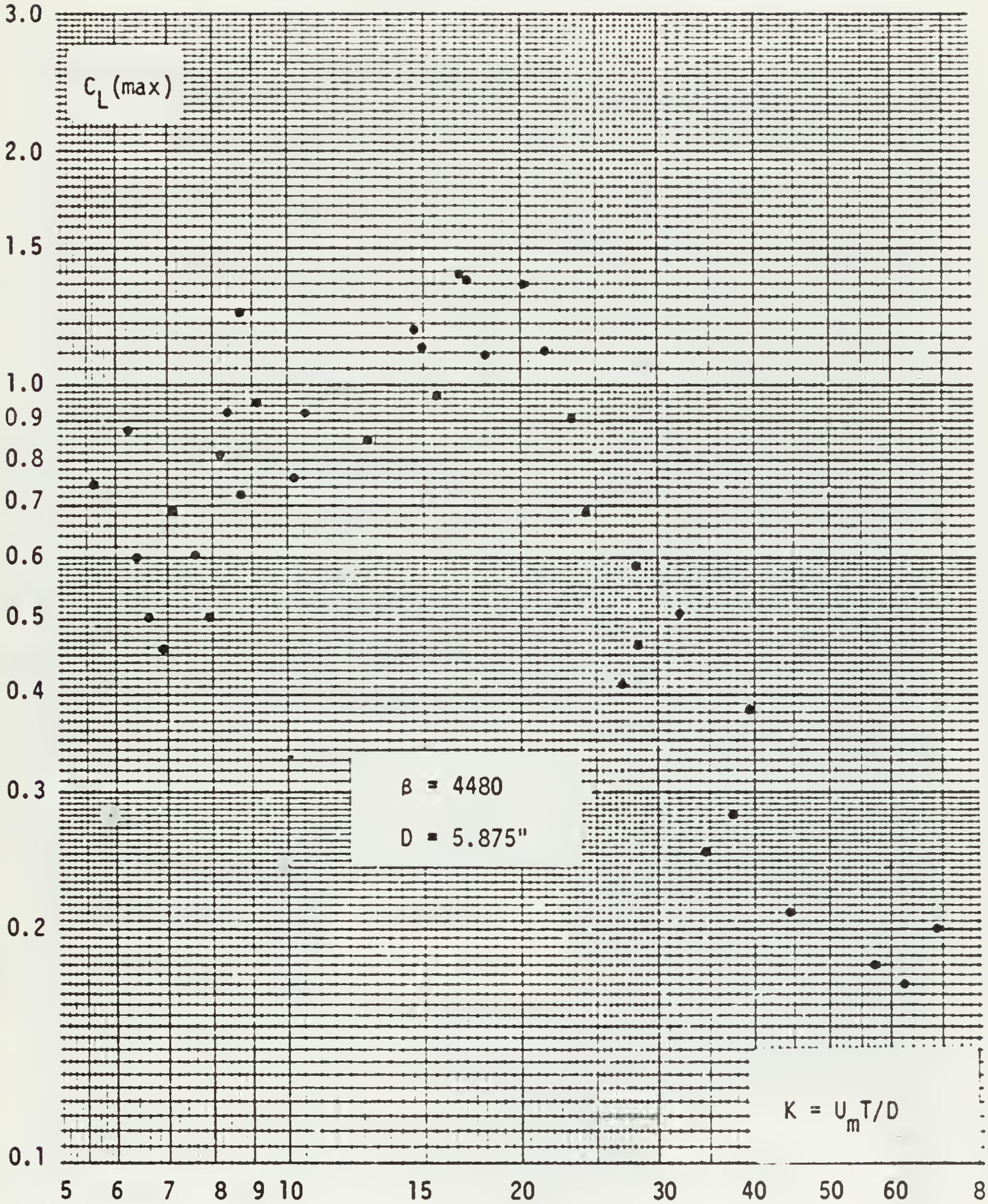

Fig. 13 C_L(max) versus K for β = 4480.

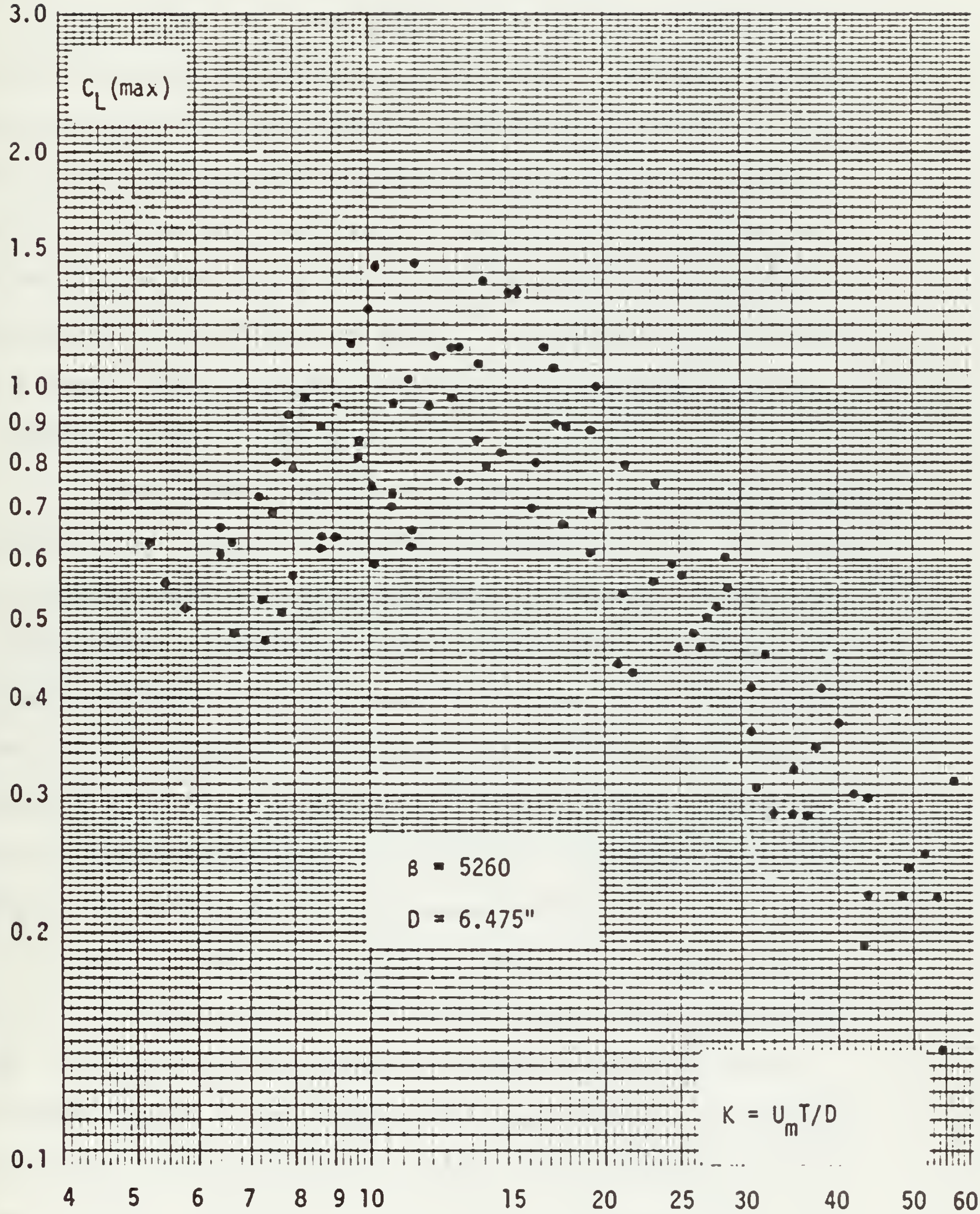

Fig. 14 C_L(max) versus K for β = 5260.

by writing $K = Re/\beta$. Prior to doing so, mean lines have been drawn through the data as meticulously as possible for each cylinder. Then round numbers such as 30,000, 40,000, etc. were chosen for Re and the corresponding K values were calculated and indicated on each plot. This simple procedure resulted in figure 15 in which CLMAX is plotted as a function of K for all smooth cylinders and the identical Reynolds number points are suitably connected. It is evident from figure 15 that there is a remarkable and heretofore unknown correlation between the force coefficient, Keulegan-Carpenter number, and the Reynolds number. The smoothness of the constant Reynolds number lines is another indication of the consistency of the data from one cylinder to another.

It is also evident from figure 15 that for a given Reynolds number CLMAX increases at first with K and then decreases gradually. The initial rise of CLMAX decreases with increasing Reynolds numbers. In fact for Re = 100,000, CLMAX decreases for K values larger than approximately 15. For a constant K, CLMAX always decreases with increasing Reynolds numbers. The most dramatic change in CLMAX relative to either K or Re occurs between K equal 8 and 30. The occurrence of the peak CLMAX values in the region of K values between K equal 10 and 25 is directly related to the shedding of the vortices as will be discussed later.

The results shown in figure 15 are replotted in figure 16 as a function of the Reynolds number for constant values of Keulegan-Carpenter numbers. This particular plot shows that CLMAX varies significantly with Reynolds numbers for Re > 20,000. This observation is in conformity with those made earlier by Sarpkaya and Tuter [5]. For Reynolds numbers from about 20,000 to 100,000 the lift coefficient decreases rapidly. For larger values of Re, lift coefficient decreases slowly once again and

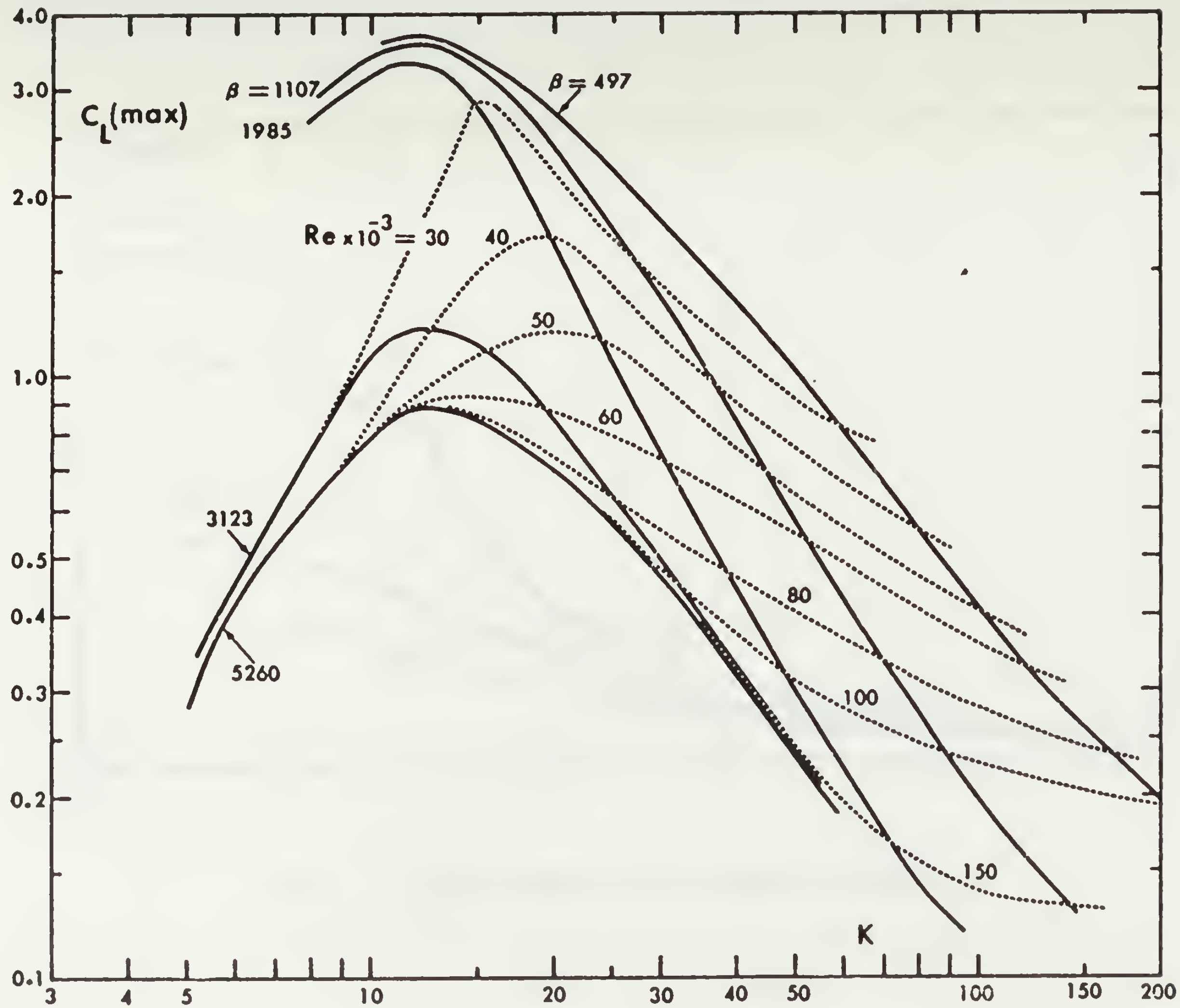

Fig. 15 C_L(max) versus K for various values of K and β.

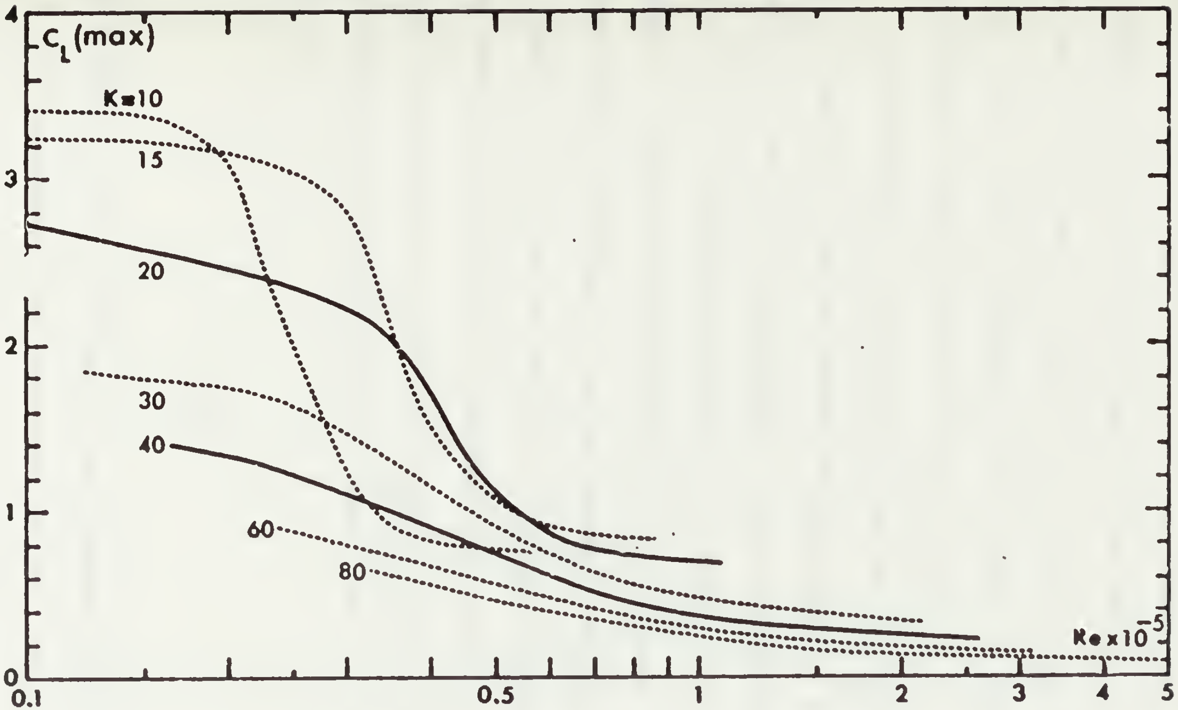

Fig. 16 C_L(max) versus Re for various values of K.

approaches a value of about 0.3 at Reynolds numbers of about 700,000. Evidently, for design purposes the transverse force has significance not only because of its magnitude, but also because of its oscillating character. Even through the ratio of the transverse force to the in-line force is not shown here, a careful examination of the data has shown that the transverse forces are of a significant fraction of the in-line forces and must necessarily be included in the force calculations through a vectorial sum of the two forces.

As noted above, the oscillatory nature of the transverse force may give rise to in-line or transverse hydro-elastic oscillations of cylindrical ocean structures whenever the natural frequency of the structure falls within approximately $\pm$ 15 percent of the vortex shedding frequency. The in-line oscillations may be excited at natural frequencies from 2 to 5 times the vortex shedding frequency. It is, therefore, essential that one has definite information about the frequency of the transverse force and its dependence, if any, on K and Re. To this end the frequency of the first harmonic of the transverse force was determined from the analog records for each β and the frequency ratio defined as

$$f_r = \frac{f_v}{1/T} \tag{12}$$

was calculated. Here f_v represents the frequency of the first harmonic and 1/T the frequency of the fluid oscillations in the tunnel. The frequency ratio f_r is shown in figure 17 in such a manner that each curve represents the highest values of K and Re below which only frequencies indicated can occur. For example, the curve indicated by A shows that

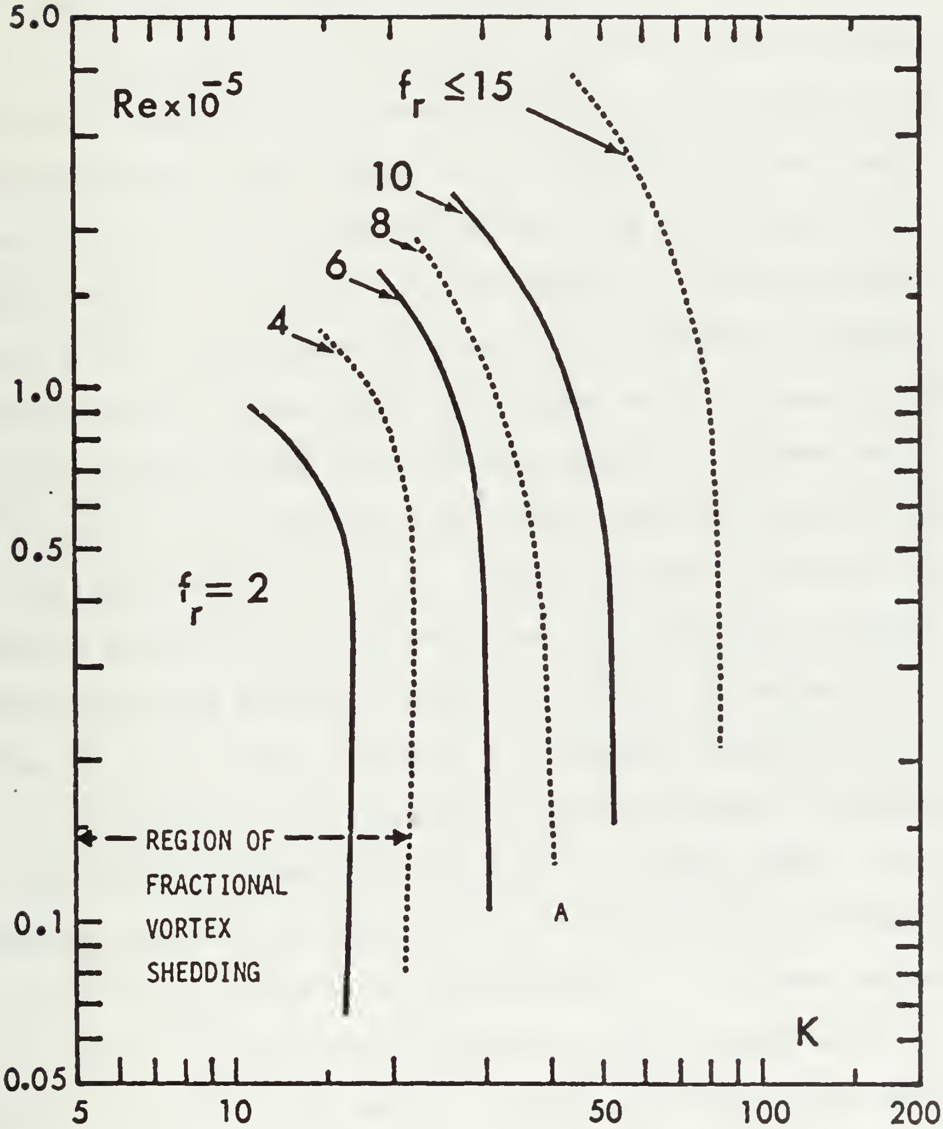

Fig. 17 Relative frequency of vortex shedding as a function of the Reynolds and Keulegan-Carpenter numbers.

to the left of this curve only the frequency ratios of 2 to 8 can occur. To the right of curve A, however, frequency ratios larger than 8 are possible. The curves for the frequency ratios 3, 5, 7, etc. have not been shown in order to simplify the presentation.

It is apparent from the foregoing discussion of the lift coefficient, the frequency of the alternating force, and the tabulated data that the lift coefficient reaches large values for relatively small values of K and Re. It is further apparent that in the region of K values (e.g. 8 < K < 15) the relative frequency of vortex shedding is not given by an integer number and that there is frequent fractional vortex shedding. In other words, the integer part of f_v shows the number of vortices actually shed while the fractional part indicates that a vortex was born, but was never shed. Such a fractional shedding leads to f_v values like 2.1 or 3.7 etc. It also shows that vortices of considerable strength can grow on one or the other side of the cylinder without ever being shed and, thereby, considerably increasing the lift force. It is, of course, true that the fractional shedding takes place at all values of K and Re; however, the larger the number of vortices the smaller is the relative significance of an unshed vortex. It is, therefore, apparent that when only two or three vortices are shed, as is the case for K values in the neighborhood of K ~ 15, then the vortices which remain attached to the cylinder give rise to significant lift forces. It should also be noted, in passing, that the in-line force is significantly effected by the fractional shedding of vortices. This becomes particularly evident from the observation of the force traces as well as from the calculation of the difference between the measured force and that predicted from the Morison equation through the use of the Fourier average coefficients.

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2. Sand-Roughened Cylinders

The tabulated data are presented in Appendix C. The same data are also plotted for each cylinder in figures 18 through 25 for two or three values of β.

A quick examination of these plots reveals that

a) the lift coefficient shows the same type of variation with K as in the case of the smooth cylinders;

b) the lift coefficient for rough cylinders is larger than that for the smooth cylinders at the corresponding Reynolds numbers; and that

c) the lift coefficient for rough cylinders does not vary with β to any appreciable extent.

A closer examination of the rough cylinder data shows that the effect of Re is almost negligible particularly for K values larger than about 15 within the range of relative roughnesses and Reynolds numbers tested.

The transverse force coefficient inevitably exhibits a larger scatter than that for the in-line force coefficients because of the somewhat random nature of the shedding of the vortices. Consequently, it is not too uncommon to obtain a variation of 20-25% for a given K value. This fact is of importance in discussing the effect of the Reynolds number on the lift coefficient.

Mean lines drawn through the data shown in figures 22 to 25 for each β are combined in figure 26. It is evident from this figure that the variation of the lift coefficient from one β to another for a given value of K is smaller than the scatter in any one of the individual plots. This shows that within the range of the parameters investigated the lift coefficient for rough cylinders does not depend on the Reynolds number. Also shown in figure 26 is the lift coefficient for smooth cylinders for β in the range 1000 to 2000. It is rather surprising

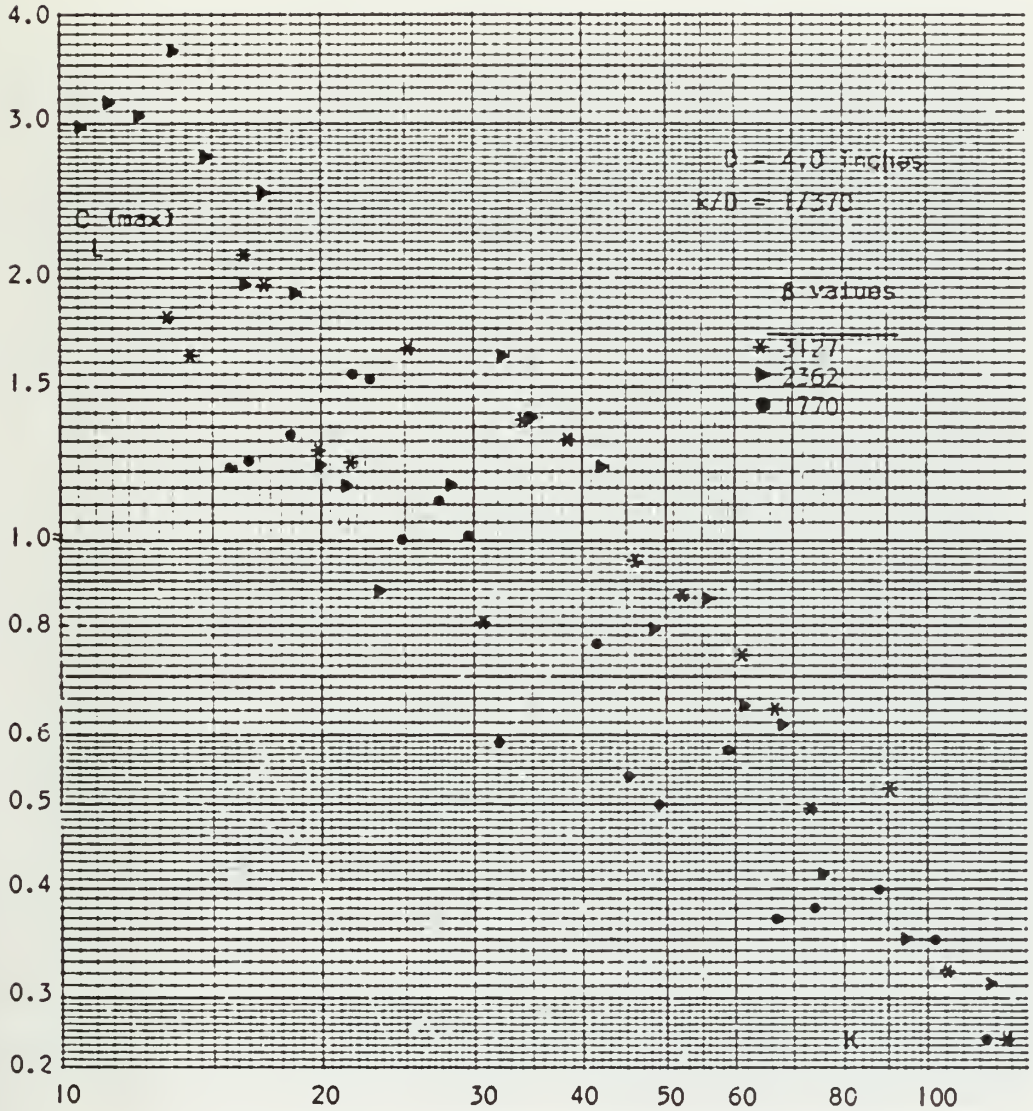

Figure 18. C_L (max) versus K for k/D = 1/370

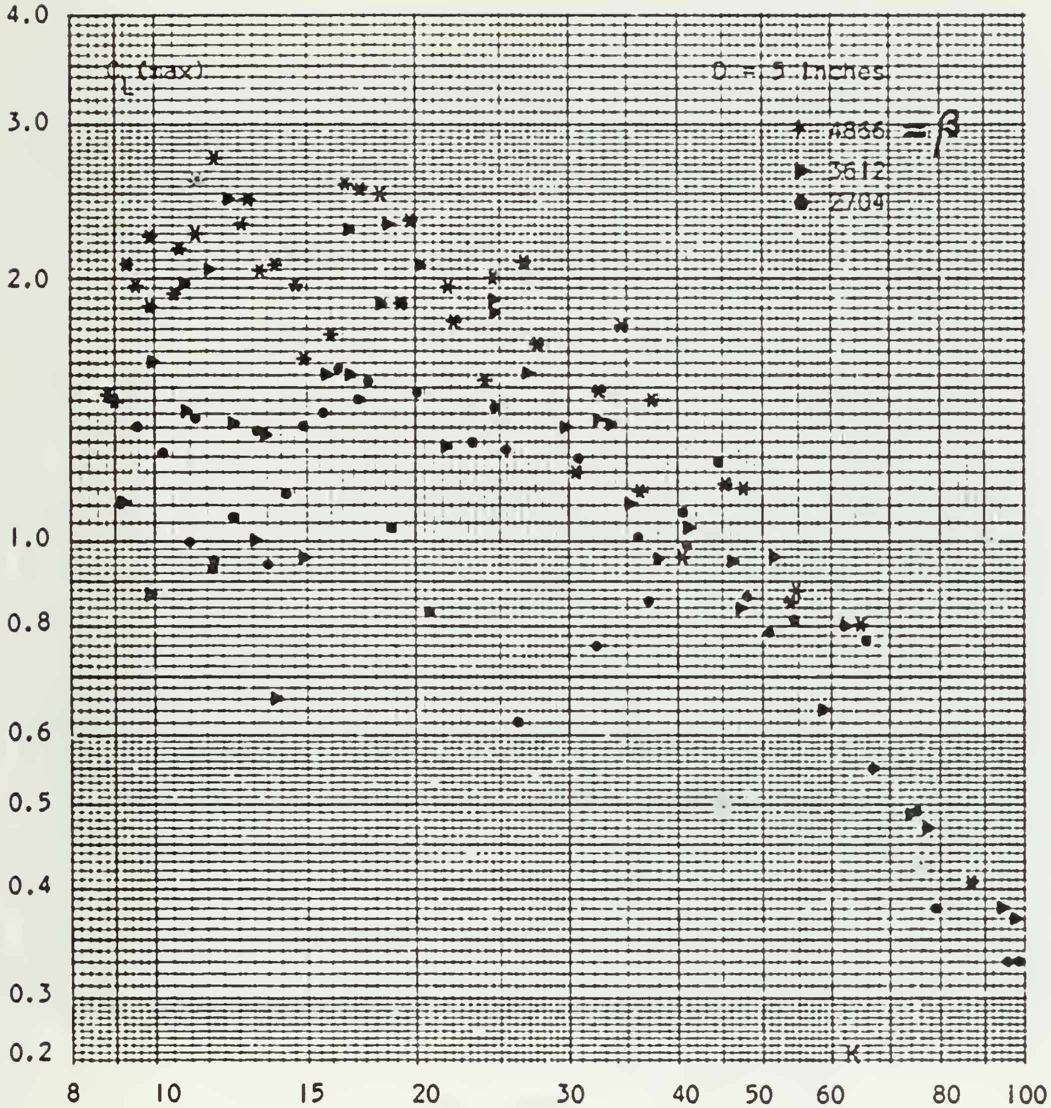

Figure 19. C_L(max) versus K for k/D = 1/370

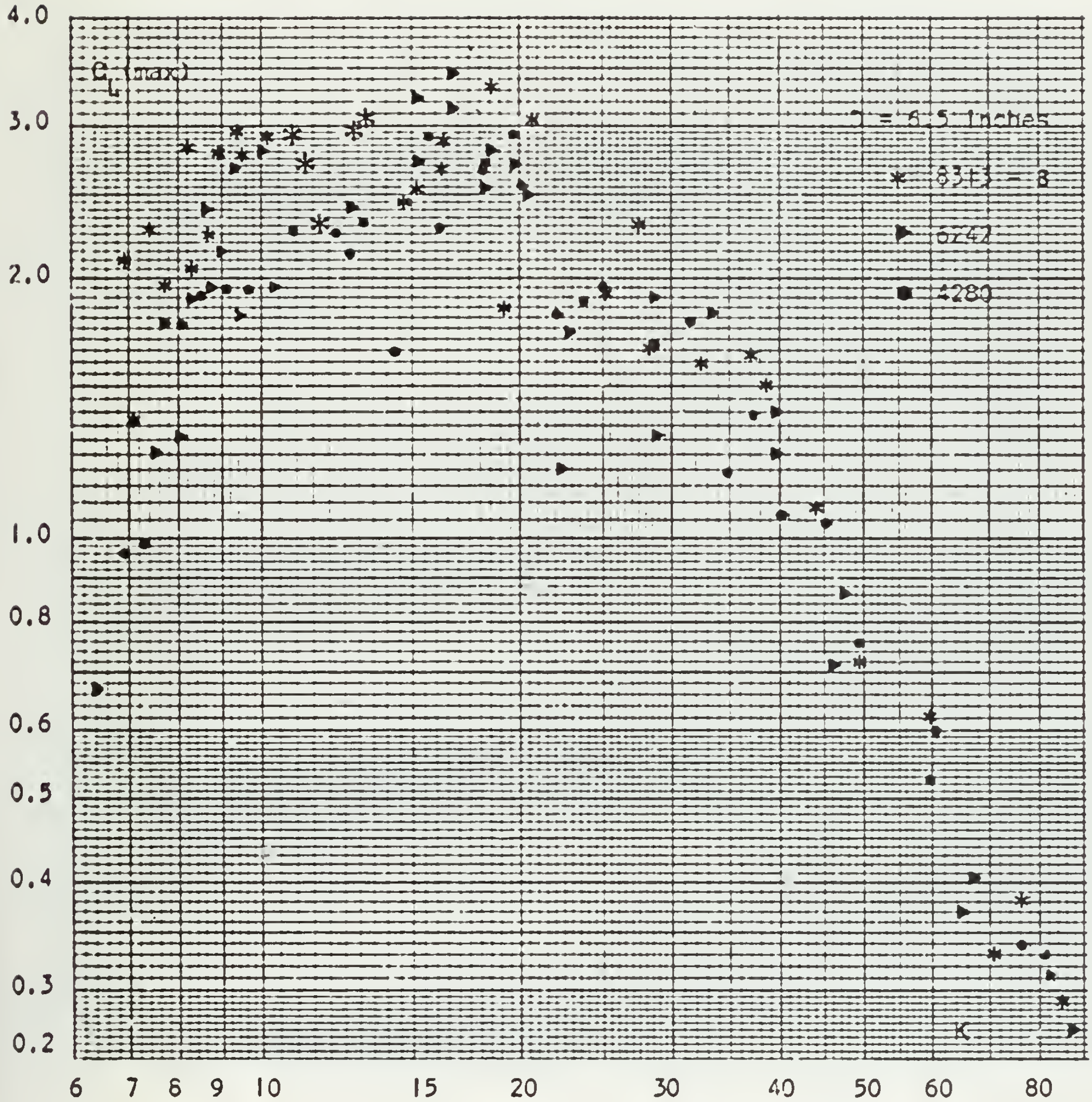

Figure 20. C_L(max) versus K for k/D = 1/370

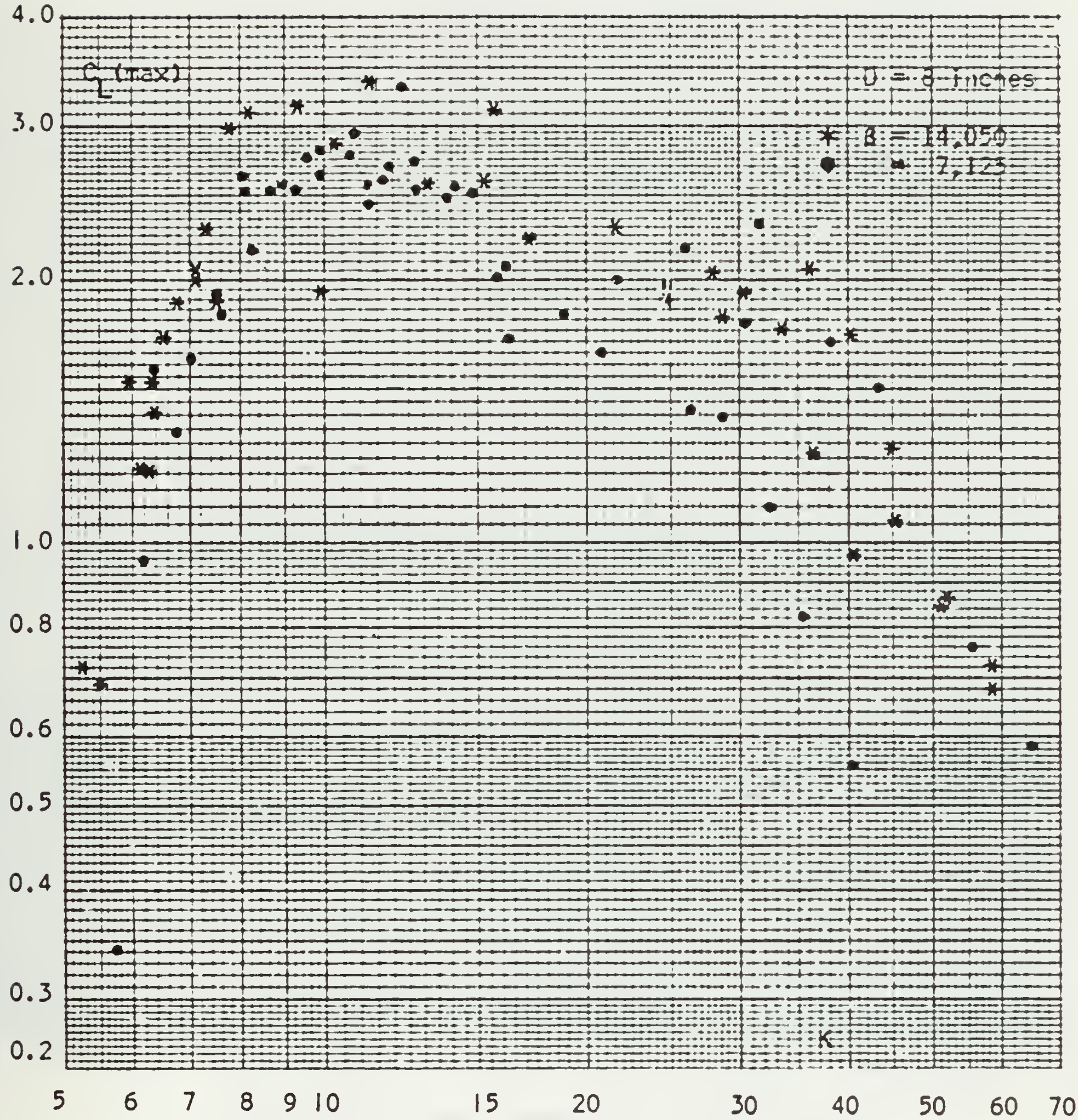

Figure 21. C_L(max) versus K for k/D = 1/370.

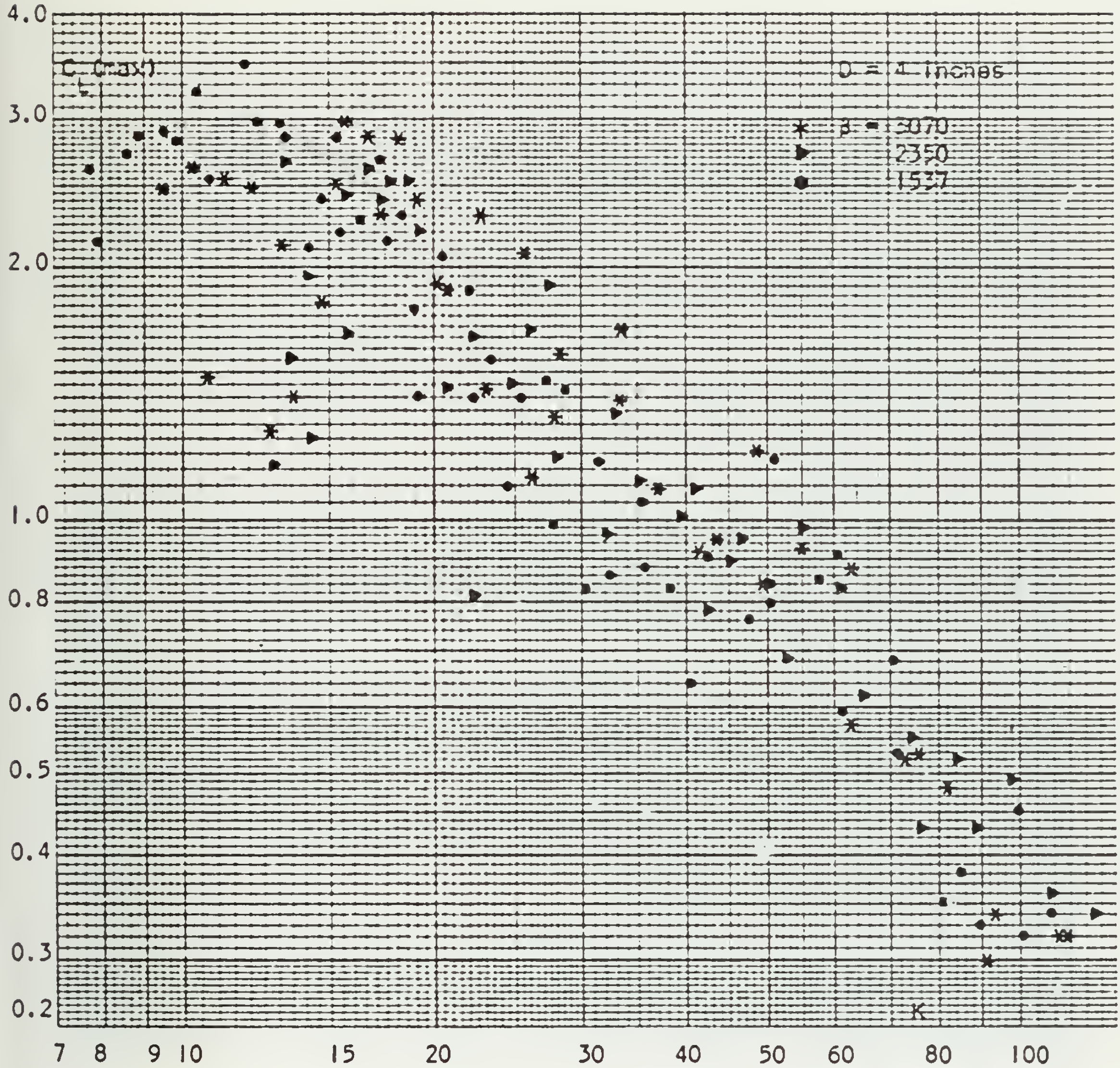

Figure 22. C_L(max) versus K for k/D = 1/195

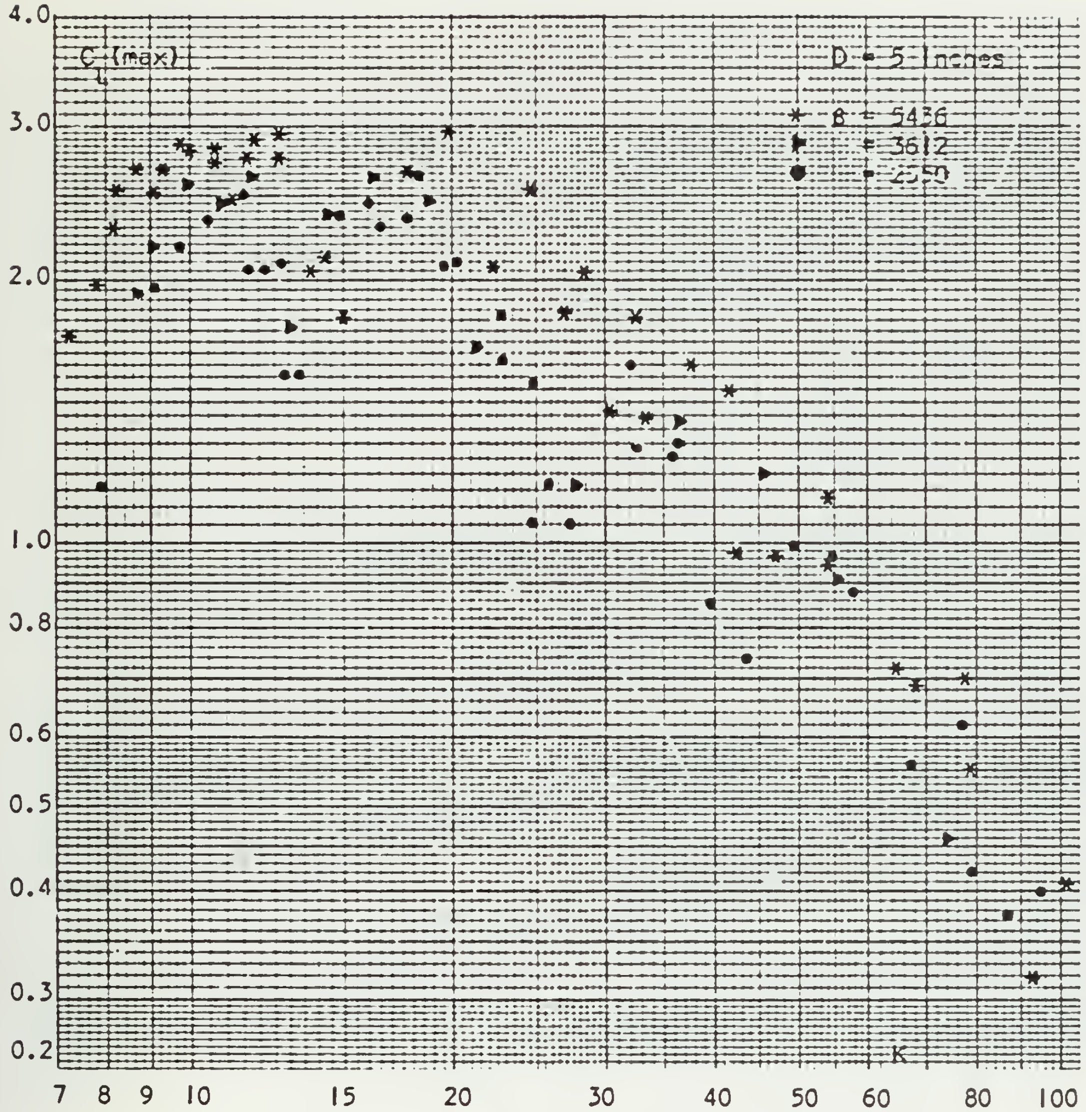

Figure 23. C_L(max) versus K for k/D = 1/195

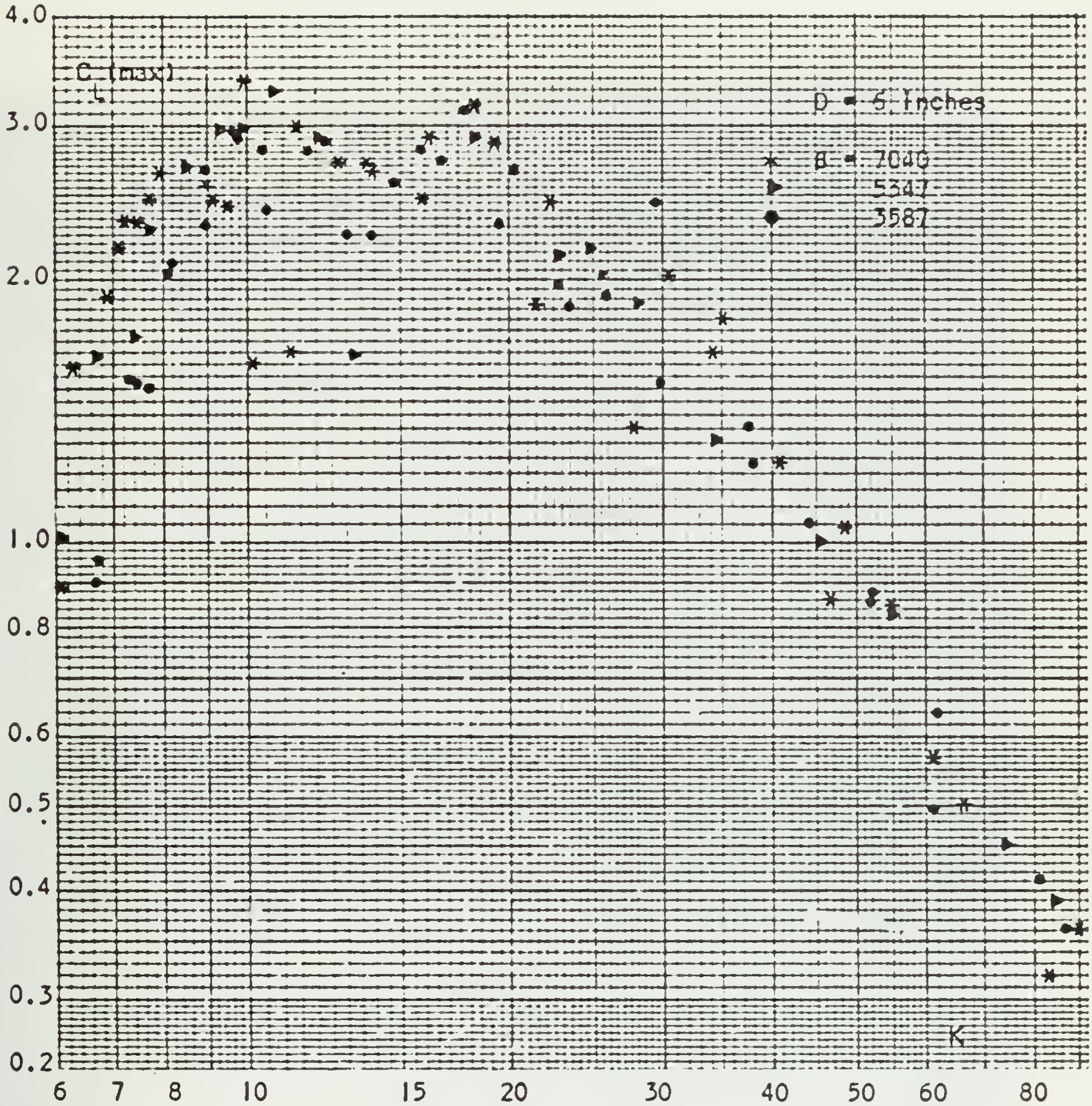

Figure 24. C_L(max) versus K for k/D = 1/195

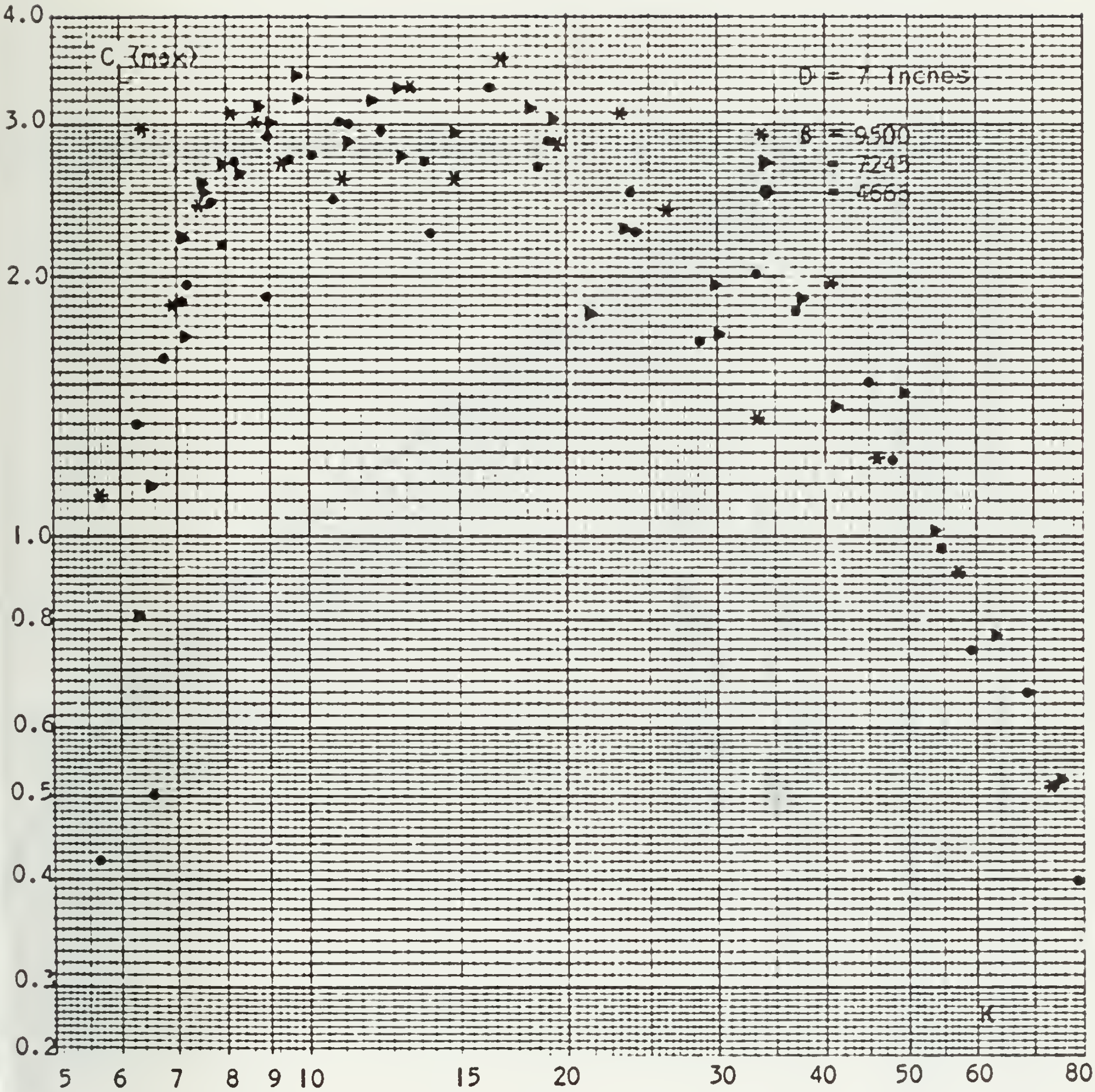

Figure 25. C_L(max) versus K for k/D = 1/195

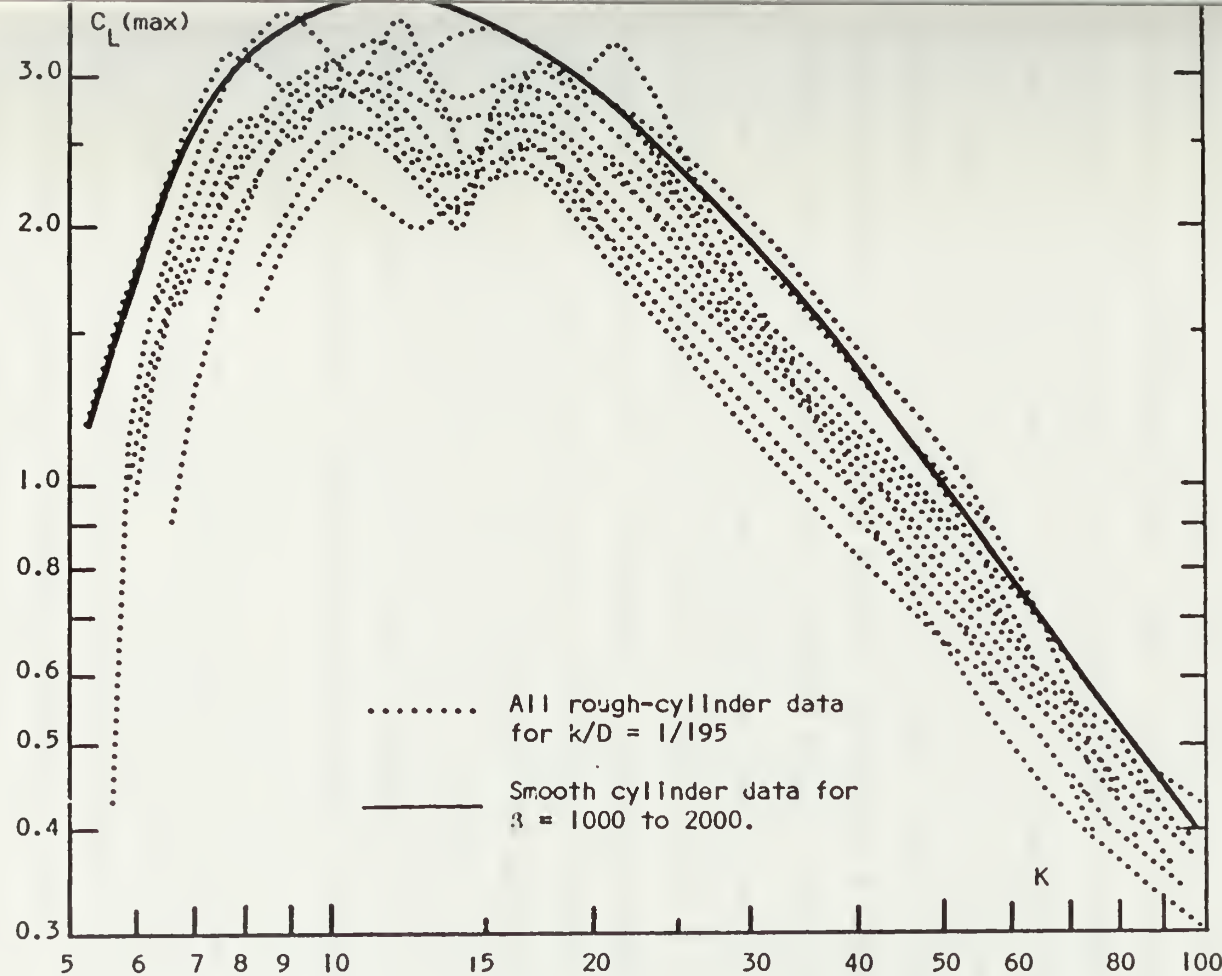

Figure 26. Combined plot of C_L(max) data for k/D = 1/195 for various values of β

that the smooth cylinder data at relatively low β values form more or less the upper limit of the rough cylinder data. Thus, the following important and somewhat surprising conclusion has been reached: for smooth cylinders, the lift coefficient depends primarily on Re and very little with K for Re larger than about 20,000. For rough cylinders, on the other hand, the lift coefficient ceases to depend on Re and varies primarily with the Keulegan-Carpenter number. Finally, the lift coefficients for rough cylinders at high Reynolds numbers are almost identical with those for smooth cylinders at very low Reynolds numbers. Even though the reasons for the foregoing are not quite clear, the consequences of this experimental finding for model testing purposes are rather obvious. Suffice it to say that roughness has a profound effect on the lift coefficient. This is partly because of the fact that it gives rise to vortices of larger strength and hence to larger lift forces, but also because the lift force for a rough cylinder is a larger fraction of the in-line force. For example, at a Reynolds number of 700,000 the drag coefficient for a rough cylinder with a relative roughness of 1/370 is about 1.4 for K = 50 and the lift coefficient at the same corresponding K and Re values is about 1.0. Thus, in all designs the vectorial sum of the in-line and transverse force will have to be taken into account. Otherwise the design force will be grossly underestimated.

As noted earlier, the alternating nature of the transverse force is as important as its magnitude. It is for this reason that the frequency of the alternating force has also been calculated, as in the case of smooth cylinders, and tabulated (see Appendices B and C). A close examination of the frequency ratios shows that f_r/K remains

essentially constant at a value of about 0.22. To be sure, there are variations from one cylinder to another and from a given combination of Re and K to another one. Nevertheless, the Strouhal number is fairly constant for all roughnesses, relative amplitudes, and Reynolds numbers larger than about 20,000.

In the foregoing, the major features of the transverse force acting on smooth and rough circular cylinders in harmonic flow have been described. It has been shown that the lift force is a significant fraction of the total force acting on the cylinder and that it is intensified by roughness. It appears that the larger shear stresses on rough cylinders give rise to vortices of stronger circulation and thereby increase the lift force. It would, therefore, be extremely interesting to measure the pressure distribution around a rigidly mounted rough cylinder and compare the results with those obtained with a smooth cylinder.

Finally, a few words are necessary regarding the application of the results presented here to the structures in the ocean environment. It is realized at the onset that the flow induced by waves is not two-dimensional and that the velocity decreases with depth and the fluid particles move on elliptical paths. The variation of the velocity along a vertical pile invariably results in a decreased correlation in the vortex shed. This in turn results in a reduced transverse force. Thus, the results presented herein must be applied with the full realization of the foregoing facts and must be regarded as the maximum upper limit of the transverse force that could be generated in wavy flows. Evidently, at great depths where the change of velocity is very small along a vertical pile, relatively large lift forces must be expected.

At elevations closer to the ocean surface, however, the rapid changes in velocity may decrease the correlation length and thus give rise to smaller transverse forces. It has been assumed that these structures have been rigid and are rigidly mounted and that there is no motion due to the forces acting on them. In general most members of such a structure are elastically mounted and that they may undergo self-excited oscillations under the action of waves and/or currents. The foregoing discussion points out not only the regions of application of the results presented herein, but also the many unsolved complex problems which are encountered in the real ocean environment. It is, therefore, suggested that further investigations be undertaken to study these hydro-elastic oscillations of smooth and rough cylinders in harmonic flows, in-line and transverse forces on yawed cylinders, and finally the effect of the wave-current combination on rigid or elastic, smooth or rough cylinders, near to or away from a wall, and normal or inclined to a two-dimensional harmonic flow.

V. CONCLUSIONS AND RECOMMENDATIONS

The extensive investigation of the transverse forces on smooth and rough circular cylinders in harmonic flow warrants the following conclusions:

1. The transverse force coefficient depends in general on both the Reynolds and Keulegan-Carpenter numbers. The variation of CLMAX with K and Re depends not only on the particular value of Re but also on the relative roughness k/D;

2. For smooth cylinders, CLMAX does not vary appreciably with Re for Re smaller than about 20,000. In this range the variation of CLMAX with K is such that it reaches a maximum at about K ~ 15 and then decreases as K increases. For Reynolds numbers between 20,000 and 150,000, CLMAX varies rapidly with Re and then gradually reaches a value of about 0.25;

3. The relative frequency of vortex shedding, when expressed in terms of the Strouhal number, shows that for Reynolds numbers smaller than about 55,000 the Strouhal number remains essentially unchanged;

4. For rough cylinders, the lift coefficient has several heretofore unknown and practically significant characteristics. The results show, within the range of the parameters tested, that CLMAX does not depend on Re. The resulting CLMAX distribution is, surprisingly enough, very close to that obtained with the smooth cylinders at very low Reynolds numbers.

5. The Strouhal number for rough cylinders remains nearly constant for all Reynolds numbers at about 0.22 with the possible exception of

those at very low Reynolds numbers. It should be emphasized that one could not have reached this conclusion had one not carried out the painstakingly difficult series of experiments described in this thesis;

6. It is recommended that pressures be measured around smooth and rough cylinders and that the effect of the self-excited oscillations of cylinders on the in-line and transverse forces be examined. It is hoped that through experiments of intrinsic quality one will be able to isolate the influence of the major factors involved and arrive at sound rules for design of structures in the ocean environment.

APPENDIX - A COMPUTER PROGRAMS

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C
C     LIFT COEFFICIENT CALCULATIONS
C
C     DIAM=CYLINDER DIAMETER
C     [illegible]OSCILLATION AMPLITUDE
C     [illegible]
C     UM=MAXIMUM VELOCITY OVER THE CYLINDER
C     CAL=CALIBRATION FACTOR
C     F[illegible]=MAXIMUM VALUE OF FORCE IN POUNDS
C     F[illegible]S=ACTUAL FORCE MEASURED IN POUNDS
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C
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      DIMENSION [illegible](55),[illegible](55)
      J=[illegible]
      DO 1 II=1,J
      [illegible]
C     PROGRAM CONSTANTS AND INITIALIZE FORCE
      [illegible]=1.9[illegible]
      [illegible]=[illegible]
      VIS=0.01[illegible]5
      PI=3.14159
      [illegible]
C     DETERMINATION OF MAX LIFT COEFFICIENT;CLEM
      DENOM=0.5*RHO*UM**2.0*DIAM*CL[illegible]
      [illegible]
      CLEM=F[illegible]/DENOM
      REYNO=UM*DIAM/VIS
      [illegible]
      BETA=UM*D[illegible]/[illegible]
C     [illegible] ACTUAL [illegible] LIFT [illegible]
      READ(5,103)(F[illegible](I),I=1,N)
      DO 10 K=1,N
      F[illegible](K)=CAL*F[illegible](K)
      [illegible]**2.0
   10 CONTINUE
      X[illegible]=N
      [illegible]=SQRT(F[illegible]/XN)
      CL[illegible]=[illegible]/[illegible]
      [illegible]
      WRITE(6,105) CLEM,CL[illegible],REYNO,[illegible]
  101 FORMAT(3F8.4,I5,3F8.4,I5)
  1[illegible] FORMAT([illegible]
     1'UM=',F7.4,2X,'CAL=',F7.4,2)X,'[illegible]=',I5)
  103 FORMAT(15F5.3)
  105 FORMAT(/,[illegible]
     1'REYNO=',F8.1,12X,'[illegible]=',F8.4,////)
    1 CONTINUE
      STOP
      END
```

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     LIFT PLOTS FOR THE U-TUNNEL
C
C     REYN= CYLINDER NUMBER
C     BK=KEULEGAN-CARPENTER NUMBER
C     CLMAX=MAXIMUM LIFT COEFFICIENT
C     CLRMS=RMS VALUE OF LIFT COEFFICIENT
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

      DIMENSION REYN(300),BK(300),CLMAX(300),CLRMS(300),RANGE(4)
      READ(5,100) NCYL
      MODCUR=1
      DO 10 I=1,NCYL
      READ(5,100) NDPT
      WRITE(6,200)
      DO 11 J=1,NDPT
      READ(5,101) NDATA,REYN(NDATA),BK(NDATA),CLMAX(NDATA),
     1CLRMS(NDATA)
      WRITE(6,21) NDATA,REYN(NDATA),BK(NDATA),CLMAX(NDATA),
     1CLRMS(NDATA)
   11 CONTINUE
      WRITE(6,202)
      RANGE(1)=300.00
      RANGE(2)=0.00
      RANGE(3)=4.50
      RANGE(4)=0.00
      CALL UTPLOT(REYN,CLMAX,NDPT,RANGE,1,MODCUR)
      WRITE(6,203)
      RANGE(3)=2.40
      CALL UTPLOT(REYN,CLRMS,NDPT,RANGE,1,MODCUR)
      WRITE(6,204)
      RANGE(1)=160.00
      RANGE(3)=4.50
      CALL UTPLOT(BK,CLMAX,NDPT,RANGE,1,MODCUR)
      WRITE(6,205)
      RANGE(3)=2.40
      CALL UTPLOT(BK,CLRMS,NDPT,RANGE,1,MODCUR)
   10 CONTINUE
  100 FORMAT(I3)
  101 FORMAT(I2,4F6.0)
  200 FORMAT('1',14X,'NDATA',6X,'REYN',9X,'BK',9X,'CLMAX',9X,
     1'CLRMS')
   21 FORMAT(' ',11X,I4,6X,F6.0,6X,F6.2,5X,F6.2,8X,F6.2)
  202 FORMAT('1',33X,'REY. CLD. NO. VS MAX LIFT COEFFICIENT',//)
  203 FORMAT('1',33X,'REY. CLD. NO. VS RMS LIFT COEFFICIENT',//)
  204 FORMAT('1',35X,'BETA VS MAX LIFT COEFFICIENT',//)
  205 FORMAT('1',35X,'BETA VS RMS LIFT COEFFICIENT',//)
      STOP
      END
```

`[illegible]`py available to DDC does not permit fully legible reproduction

SPECIAL NOTES FOR APPENDICES B AND C

The data given in the following tables are identified with the diameter of the cylinder, relative roughness, and the frequency parameter.

The following symbols have been used:

DIAM - diameter of the test cylinder

k - height of sand roughness

D - diameter of the test cylinder

β - frequency parameter ($D^2/\nu T$)

REYN - Reynolds number ($U_m D/\nu$)

UMTOD - Keulegan-Carpenter number ($U_m T/D$)

CLMAX - maximum lift coefficient (see eqn. 1)

FR - frequency ratio (see eqn. 3)

ST - Strouhal number (see eqn. 4)

APPENDIX - B TRANSVERSE FORCE DATA FOR SMOOTH CYLINDERS

DIAM =2.0" k/D =0.0 β=497

REYN	UMTOD	CLMAX	FR	ST
88.24	177.49	0.15	44	0.25
87.28	175.55	0.22	35	0.20
80.12	161.16	0.24	27	0.17
79.02	158.93	0.26	27	0.17
72.56	146.76	0.24	28	0.19
66.43	137.64	0.28	27	0.20
66.50	133.76	0.32	27	0.20
60.58	121.84	0.39	25	0.20
58.92	118.51	0.33	22	0.19
55.06	110.75	0.24	23	0.21
54.65	109.93	0.47	21	0.19
51.60	103.79	0.46	21	0.20
47.95	96.45	0.55	17	0.13
46.29	93.11	0.50	18	0.19
44.36	90.22	0.33	19	0.20
42.22	84.92	0.58	15	0.18
41.93	84.34	0.43	13	0.21
38.91	78.24	0.59	15	0.19
38.52	77.45	0.76	16	0.21
36.80	74.02	0.61	15	0.22
35.71	71.83	0.39	14	0.19
34.27	70.14	0.44	14	0.20
33.50	67.37	0.58	14	0.21
33.12	66.61	1.14	14	0.21
32.28	64.93	0.76	14	0.22
30.68	61.72	0.81	13	0.21
30.35	61.05	0.81	14	0.23
28.98	58.28	0.75	11	0.19
28.92	58.15	0.86	13	0.22
27.81	55.93	0.76	12	0.21
27.21	54.72	1.39	13	0.24
26.70	53.71	0.95	12	0.22
25.77	51.83	1.27	10	0.19
25.66	51.61	1.00	11	0.21
25.11	50.50	1.41	10	0.20
23.54	47.35	0.89	9	0.19
24.29	48.85	1.21	10	0.20
23.43	47.13	0.77	13	0.20
22.66	45.57	1.71	9	0.20
22.39	45.03	1.75	10	0.22
21.43	43.09	1.01	9	0.21
20.79	41.82	1.63	8	0.19
20.43	41.08	1.29	8	0.19
20.13	40.49	1.79	8	0.20
19.43	39.07	1.12	9	0.22
19.36	38.93	1.59	8	0.20
18.50	37.21	1.80	8	0.21
18.06	36.32	1.21	7	0.19
17.79	35.78	1.79	8	0.22
17.35	34.89	1.38	7	0.20

DIAM =2.0"   k/D =0.0 β=497

16.83	33.05	1.60	9	0.24
16.23	32.34	1.67	8	0.24
15.32	30.65	1.19	7	0.2[illegible]
15.26	30.70	1.51	7	0.23
14.98	31.13	1.93	7	0.22
14.65	29.43	1.73	6	0.20
14.22	28.60	1.66	6	0.21
13.80	27.67	2.05	6	0.21
13.59	27.33	1.80	6	0.22
13.19	25.54	1.73	5	0.23
12.26	24.66	1.60	5	0.20
10.52	21.16	2.55	5	0.24
10.21	20.53	2.10	5	0.24
10.11	20.34	2.21	4	0.25
9.76	19.54	2.21	5	0.25
9.67	19.45	2.52	4	0.21
9.35	18.31	2.73	4	0.21
9.24	18.59	2.30	4	0.21
9.01	18.11	3.20	4	0.22
8.75	17.61	3.24	4	0.23
8.61	17.32	2.78	4	0.23
8.31	16.72	3.41	4	0.24
8.29	16.68	2.86	4	0.24
8.06	16.21	3.17	3	0.13
7.98	16.05	3.16	4	0.25
7.70	15.48	3.25	3	0.19
7.55	15.12	3.34	3	0.20
7.43	14.94	2.92	3	0.20
7.14	14.36	2.46	3	0.21
7.14	14.36	2.39	3	0.21
6.91	13.89	2.35	2	0.14
6.75	13.57	3.15	2	0.15
6.46	13.00	3.71	2	0.15
6.20	12.49	3.83	2	0.16
6.04	12.14	3.07	2	0.1[illegible]
5.85	11.76	3.64	2	0.17

DIAM=2.5" k/D =0.0 β=784

REYN	UMTOD	CLMAX	FR	ST
109.60	139.81	0.24	27	0.19
98.54	125.71	0.26	27	0.21
89.02	113.57	0.34	21	0.18
81.09	103.44	0.25	21	0.20
71.74	91.5[illegible]	0.41	21	0.23
66.21	84.46	0.34	18	0.21
62.58	79.83	0.38	13	0.16
56.46	72.03	0.41	11	0.15
51.68	65.93	0.49	13	0.20
47.46	60.54	0.61	12	0.20
43.31	55.25	0.55	11	0.20
36.66	46.77	0.93	10	0.21
34.36	43.[illegible]	0.92	10	0.23
30.30	38.72	1.24	9	0.23
27.38	34.93	1.50	7	0.20
26.25	33.48	1.63	7	0.21
25.04	31.94	1.71	7	0.22
24.03	30.65	1.83	6	0.20
21.86	27.89	1.93	6	0.22
20.85	26.60	1.54	6	0.23
19.72	25.16	1.50	6	0.24
18.27	23.31	2.42	5	0.21
17.34	22.12	2.09	5	0.23
16.47	21.01	2.69	[illegible]	0.19
15.71	20.04	3.19	5	0.25
15.02	19.16	2.79	4	0.21
14.46	18.43	3.07	4	0.22
13.81	17.62	3.27	4	0.23
13.19	16.8[illegible]	3.71	3	0.18
12.72	16.22	3.39	3	0.18
12.26	15.64	3.30	3	0.19
11.75	14.98	2.44	2	0.15
10.79	13.77	2.51	2	0.15
10.22	13.15	3.17	2	0.15
9.84	12.55	2.94	2	0.16
9.29	11.84	3.05	2	0.17
8.77	11.1[illegible]	3.13	2	0.18
8.31	10.[illegible]	3.25	2	0.19
7.94	10.12	3.50	2	0.20
7.52	9.5[illegible]	3.42	2	0.21
7.10	9.06	3.56	2	0.22
6.90	8.81	3.67	2	0.23

DIAM=3.0"   k/D =0.0 β=1106

REYN	UMTCD	CLMAX	FR	ST	CLRMS
162.26	146.61	0.03	29	0.20	0.04
158.78	143.43	0.04	24	0.17	0.03
143.36	129.55	0.10	20	0.16	0.04
138.00	124.70	0.18	20	0.16	0.06
125.49	113.41	0.16	18	0.18	0.05
118.10	106.70	0.17	17	0.16	0.07
111.73	100.97	0.23	17	0.17	0.07
102.10	92.23	0.23	19	0.21	0.10
98.58	89.09	0.24	14	0.16	0.10
89.34	80.73	0.23	14	0.13	0.11
88.94	80.37	0.34	15	0.19	0.13
80.10	72.33	0.32	14	0.20	0.12
79.44	71.77	0.32	13	0.15	0.17
69.02	62.37	0.52	14	0.23	0.19
65.36	59.05	0.41	12	0.20	0.15
62.72	56.63	0.69	12	0.21	0.24
59.28	53.57	0.44	12	0.23	0.14
58.35	53.27	0.51	12	0.23	0.17
54.50	49.25	0.84	10	0.21	0.33
49.41	44.65	0.66	9	0.21	0.27
46.34	41.87	1.10	10	0.23	0.37
44.46	40.16	1.00	9	0.22	0.49
42.81	38.63	0.86	9	0.22	0.35
40.59	36.66	0.93	8	0.22	0.38
38.04	34.31	0.94	7	0.19	0.42
37.89	34.22	0.74	7	0.21	0.32
32.93	29.76	0.96	6	0.19	0.33
32.48	29.35	1.46	6	0.19	0.67
29.94	27.03	1.57	5	0.20	0.81
29.58	26.73	1.22	6	0.21	0.51
27.90	25.21	2.22	5	0.20	0.74
27.48	24.84	1.67	5	0.21	0.74
26.59	24.02	2.25	5	0.21	0.91
25.65	23.18	1.96	5	0.22	0.93
25.43	22.97	1.71	5	0.21	0.68
23.93	21.60	1.98	5	0.22	0.87
23.83	21.54	2.27	5	0.21	0.88
22.65	20.46	2.59	5	0.22	1.02
22.55	20.39	2.63	4	0.19	1.01
21.33	19.27	2.92	4	0.22	1.13
20.39	18.43	3.16	4	0.23	1.29
19.16	17.31	2.27	4	0.25	1.16
18.08	16.35	2.95	4	0.21	1.18
18.06	16.32	2.51	2	0.15	1.05
17.14	15.49	2.27	3	0.21	1.21
16.95	15.32	3.15	2	0.14	1.35
15.63	14.12	3.72	2	0.15	1.45
14.57	13.15	3.10	2	0.15	1.50
14.57	13.16	3.26	2	0.16	1.55
13.65	12.34	3.10	2	0.16	1.65
13.22	11.95	3.76	2	0.13	1.72
13.00	11.73	3.24	2	0.13	1.67
11.76	10.63	3.33	2	0.23	1.73
10.70	9.67	3.86	2	0.24	1.83
10.14	9.14	2.53	2	0.22	1.53
9.43	8.53	3.17	2	0.27	1.72
8.72	7.37	2.40	2	0.26	1.45
8.13	7.35	[illegible]	2	0.31	1.53

DIAM=4.0"   k/D =0.0 β=1985

REYN	UNTCD	CLMAX	FO	ST	CLRMS
194.31	97.84	0.12	24	0.26	0.04
183.78	92.59	0.14	19	0.25	0.05
165.06	83.14	0.12	22	0.26	0.05
149.30	75.12	0.20	21	0.23	0.07
144.95	73.05	0.17	20	0.21	0.08
130.67	65.31	0.13	19	0.30	0.08
115.55	58.13	0.23	13	0.23	0.10
112.24	56.54	0.26	14	0.25	0.11
102.32	51.54	0.27	16	0.32	0.09
101.79	51.27	0.30	12	0.23	0.12
92.85	46.76	0.25	11	0.23	0.11
87.67	44.15	0.33	10	0.23	0.14
84.90	42.73	0.32	12	0.23	0.15
82.46	41.54	0.53	10	0.25	0.16
77.07	38.33	0.47	12	0.30	0.16
74.98	37.77	0.55	9	0.24	0.19
70.34	35.42	0.62	5	0.25	0.24
67.03	33.75	[illegible]	[illegible]	0.23	0.24
65.07	32.77	0.67	9	0.28	0.24
64.22	32.35	0.75	7	0.22	0.31
60.43	30.44	0.61	7	0.27	0.22
58.79	29.61	0.76	7	0.23	0.28
56.22	28.32	1.01	5	0.22	0.43
54.24	27.32	1.07	5	0.21	0.45
52.16	26.27	0.85	6	0.23	0.34
47.43	23.10	1.50	5	0.23	0.66
46.69	23.52	1.51	5	0.21	0.65
45.53	22.93	1.36	5	0.23	0.59
43.59	22.30	1.79	[illegible]	0.23	0.67
42.43	21.37	1.52	4	0.19	0.68
41.20	20.75	0.91	5	0.22	0.48
39.12	19.90	1.32	4	0.22	0.65
37.92	19.10	1.45	4	0.23	0.51
35.17	17.72	1.95	3	0.14	0.33
33.09	16.67	2.78	2	0.14	1.06
30.79	15.51	2.31	3	0.13	1.12
29.11	14.65	[illegible]	2	0.14	1.37
26.93	13.57	3.03	3	0.15	1.57
24.24	12.22	2.53	2	0.15	1.31
22.34	11.30	3.30	2	0.19	1.73
21.22	10.69	2.98	2	0.19	1.75
19.69	9.91	2.34	2	0.22	1.75
16.70	8.44	2.95	2	0.24	1.80

DIAM=5.0"   k/D =0.0 β=3123

REYN	UMICD	CLMAX	FR	ST	CLRMS
210.47	67.38	0.15	16	0.24	0.05
185.64	59.44	0.13	18	0.30	0.06
181.17	58.00	0.20	19	0.32	0.07
168.38	53.91	0.19	19	0.35	0.07
153.39	49.27	0.27	17	0.36	0.09
151.15	48.39	0.20	19	0.39	0.05
139.75	44.74	0.24	16	0.36	0.09
134.56	43.08	0.25	14	0.32	0.10
122.48	39.22	0.31	12	0.31	0.12
114.13	37.41	0.31	13	0.31	0.14
108.03	34.59	0.50	9	0.25	0.22
106.76	34.18	0.27	11	0.21	0.12
96.82	31.00	0.38	9	0.24	0.15
95.44	30.55	0.45	7	0.22	0.19
87.56	28.03	0.34	8	0.28	0.17
82.29	26.34	0.79	7	0.26	0.25
80.51	25.78	0.64	7	0.27	0.28
75.80	24.27	0.51	6	0.23	0.24
71.91	23.03	0.49	6	0.25	0.13
69.85	22.36	0.83	5	0.22	0.36
65.70	21.03	0.69	4	0.19	0.25
62.25	19.93	1.05	5	0.25	0.42
57.82	18.51	1.02	4	0.23	0.42
57.13	18.31	1.00	4	0.23	0.45
54.29	17.38	1.07	3	0.18	0.37
53.74	17.21	0.74	4	0.22	0.33
50.17	16.06	0.67	3	0.14	0.50
45.26	14.49	1.25	3	0.21	0.66
43.40	13.90	0.99	3	0.21	0.52
42.25	13.52	1.25	3	0.22	0.66
35.48	11.36	1.22	2	0.19	0.72
33.58	10.38	0.93	2	0.18	0.51
32.23	10.32	1.22	2	0.20	0.75
31.88	10.21	1.03	2	0.21	0.60

DIAM=6.0"   k/D =0.0   β=4480

REYN	LMTCD	CLMAX	FR	ST	CLRMS
307.05	68.52	0.20	23	0.33	0.08
~~256.21~~	~~57.15~~	~~0.13~~	~~15~~	~~0.26~~	~~0.08~~
198.35	44.27	0.21	17	0.38	0.08
177.71	39.65	0.33	14	0.35	0.14
~~154.55~~	~~34.57~~	~~0.25~~	~~11~~	~~0.32~~	~~0.05~~
129.20	28.83	0.46	10	0.31	0.18
113.78	[illegible]	0.53	9	0.29	0.25
104.34	23.29	0.90	7	0.23	0.33
96.09	21.44	1.11	6	0.25	0.40
~~80.82~~	~~18.04~~	~~1.33~~	~~5~~	~~0.23~~	~~0.47~~
74.70	16.67	1.38	5	0.27	0.59
69.67	15.54	0.96	4	0.24	0.42
~~64.98~~	~~14.50~~	~~1.13~~	~~3~~	~~0.22~~	~~0.59~~
47.48	10.59	0.92	3	0.30	0.43
41.17	9.19	0.93	3	0.22	0.39
36.33	8.11	0.81	2	0.26	0.35
34.01	7.58	0.60	2	0.32	0.27
~~31.78~~	~~7.09~~	~~0.69~~	~~2~~	~~0.28~~	~~0.29~~
29.69	6.62	0.50	2	0.27	0.26
25.09	5.60	0.74	2	0.39	0.31

DIAM=6.0" k/D =0.0 β=4480

REYN	UMTOD	CLMAX	FR	ST
279.36	62.37	0.17	20	0.32
168.19	37.55	0.28	13	0.35
143.95	32.14	0.51	10	0.31
120.71	26.95	0.41	8	0.30
109.18	24.38	0.68	6	0.25
90.92	20.30	1.34	5	0.25
76.69	17.12	1.37	4	0.23
67.11	14.44	1.12	4	0.27
56.73	12.66	0.85	4	0.31
46.05	10.28	0.76	3	0.29
39.13	8.74	0.72	2	0.23
37.80	8.44	0.92	2	0.24
35.43	7.91	0.50	2	0.25
30.78	6.87	0.46	2	0.29
28.84	6.44	0.60	2	0.31

DIAM=6.5"   k/D =0.0 β=5261

REYN	UMTED	CLMAX	FR	ST	CLRMS
282.08	53.62	0.22	14	0.26	0.08
276.74	53.61	0.25	21	0.40	0.09
230.33	43.84	0.29	13	0.30	0.12
221.18	42.05	0.20	16	0.38	0.10
201.50	38.30	0.41	9	0.23	0.13
190.30	36.18	0.28	8	0.21	0.10
183.62	34.90	0.25	11	0.32	0.12
163.88	31.15	0.36	10	0.31	0.13
163.01	30.99	0.41	9	0.28	0.15
149.00	28.32	0.52	9	0.31	0.20
136.39	25.93	0.48	8	0.20	0.23
132.28	25.15	0.57	7	0.23	0.19
114.88	21.84	0.43	7	0.30	0.20
110.39	21.00	0.54	2	0.11	0.23
101.39	19.27	0.87	2	0.11	0.33
100.52	19.11	0.61	2	0.17	0.23
91.89	17.47	0.89	2	0.12	0.40
90.65	17.23	1.07	3	0.15	0.45
85.41	16.24	0.79	3	0.19	0.32
81.30	15.46	1.33	3	0.19	0.45
79.50	15.11	1.31	3	0.21	0.64
74.93	14.24	0.78	2	0.21	0.43
73.90	14.02	1.36	2	0.17	0.63
69.33	13.17	0.75	2	0.15	0.43
67.06	12.75	1.12	3	0.20	0.53
64.39	12.24	0.55	2	0.16	0.51
60.54	11.50	1.44	3	0.22	0.61
58.12	11.05	1.02	3	0.27	0.39
56.17	10.83	0.70	2	0.34	0.37
54.11	10.29	1.41	2	0.18	0.58
52.78	10.03	1.25	2	0.16	0.46
50.26	9.55	1.14	2	0.20	0.47
47.59	9.05	0.64	3	0.28	0.25
45.79	8.71	0.62	3	0.31	0.27
45.79	8.70	0.39	2	0.20	0.39
42.04	8.00	0.57	3	0.31	0.29
41.32	7.85	0.51	2	0.29	0.28
39.78	7.57	0.69	2	0.23	0.30
38.54	7.33	0.47	2	0.25	0.30
33.61	6.39	0.66	2	0.32	0.43
30.42	5.78	0.52	2	0.47	0.35
28.68	5.45	0.56	2	0.23	0.40
27.29	5.19	0.63	2	0.31	0.44

DIAM=6.5" k/D =0.0 β=5261

REYN	UMTOD	CLMAX	FQ	ST
294.62	56.01	0.31	15	0.27
287.01	54.56	0.14	15	0.27
261.06	49.63	0.24	18	0.36
254.79	48.44	0.22	18	0.37
233.31	44.36	0.22	15	0.34
228.38	43.42	0.19	15	0.34
210.91	40.10	0.37	13	0.32
197.03	37.46	0.34	12	0.32
184.03	34.99	0.32	9	0.26
173.75	33.03	0.28	10	0.30
168.82	32.09	0.45	9	0.28
162.44	30.88	0.31	9	0.29
153.30	29.14	0.55	10	0.34
150.93	28.69	0.60	9	0.31
142.15	27.02	0.51	9	0.33
139.97	26.61	0.45	7	0.26
130.48	24.81	0.46	7	0.28
128.68	24.46	0.59	7	0.29
122.05	23.20	0.75	8	0.34
120.77	22.96	0.56	6	0.26
111.62	21.22	0.79	6	0.28
109.67	20.85	0.44	6	0.29
103.04	19.59	1.00	6	0.31
101.03	19.21	0.69	5	0.26
94.40	17.95	0.88	5	0.28
93.68	17.81	0.66	5	0.28
87.30	16.72	1.11	4	0.24
84.54	16.07	0.69	4	0.25
82.74	15.73	1.59	4	0.25
77.09	14.65	0.81	4	0.27
72.46	13.77	0.83	3	0.22
72.31	13.75	1.06	3	0.22
68.50	13.02	1.13	3	0.23
68.19	12.96	0.96	3	0.23
63.88	12.14	1.09	3	0.25
62.95	11.97	0.94	3	0.25
60.18	11.44	0.65	3	0.26
59.82	11.37	0.62	3	0.26
56.44	10.73	0.71	2	0.19
56.27	10.70	0.95	3	0.28
53.39	10.15	0.74	3	0.30
53.29	10.15	0.59	2	0.20
50.83	9.67	0.35	2	0.21
50.88	9.57	0.81	3	0.31
47.99	9.12	0.94	3	0.32
45.64	8.67	0.63	2	0.23
43.89	8.34	0.97	2	0.24
42.04	7.99	0.78	2	0.25
41.42	7.87	0.92	2	0.25
39.98	7.60	0.80	2	0.26
38.18	7.26	0.53	2	0.27
38.03	7.23	0.72	2	0.28
36.90	7.01	0.61	2	0.28
35.31	6.71	0.48	2	0.30
35.20	6.69	0.63	2	0.30
33.66	6.40	0.61	2	0.31

DIAM = 8.0"   k/D = 0.0 β= 7134

REYN	UMTOD	CLMAX	FR	ST
497.86	69.79	0.17	20.4	0.29
497.29	69.72	0.15	22.3	0.32
433.27	60.74	0.25	18.4	0.30
412.12	57.77	0.23	22.0	0.38
366.39	51.36	0.23	21.2	0.41
355.53	49.84	0.27	13.3	0.28
328.67	46.07	0.20	19.7	0.42
320.09	44.87	0.28	12.8	0.29
290.08	40.57	0.27	15.3	0.38
284.08	39.82	0.29	12.2	0.31
241.21	33.81	0.26	10.6	0.31
240.07	33.65	0.47	12.0	0.36
216.19	30.31	0.49	7.9	0.26
201.21	28.21	0.30	9.8	0.35
193.31	27.10	0.41	7.1	0.26
171.12	23.99	0.54	6.6	0.27
170.55	23.91	0.50	7.3	0.31
158.54	22.23	0.51	6.9	0.31
153.23	21.49	0.73	6.5	0.30
134.18	18.81	0.46	5.7	0.30
130.40	18.28	0.77	4.9	0.27
120.56	16.90	0.84	5.7	0.33
114.16	16.00	0.63	4.4	0.28
112.44	15.76	0.76	5.3	0.34
104.36	14.63	1.02	4.2	0.29
99.52	13.95	0.74	3.6	0.26
94.32	13.22	0.80	3.6	0.27
90.58	12.70	0.80	3.0	0.24
80.35	11.26	1.30	2.1	0.19
77.55	10.87	0.63	2.1	0.19
75.39	10.57	1.49	2.0	0.19
70.38	9.94	1.72	2.0	0.21
67.29	9.43	0.46	[illegible]	0.23
66.83	9.37	1.80	2.1	0.23
61.93	8.68	1.20	2.0	0.23
61.70	8.65	0.68	2.0	0.24
54.74	7.67	0.32	2.3	0.30
54.40	7.63	0.46	2.1	0.27
52.85	7.41	0.54	2.1	0.28
50.65	7.10	0.80	2.0	0.29
47.58	6.73	0.46	2.1	0.31
47.09	6.60	0.67	2.1	0.32
43.77	6.13	0.54	2.0	0.33

DIAM = 8.0" k/D = 0.0 β= 13,908

PEYN	UMTOD	CLMAX	FR	ST
950.60	68.35	0.19	28.9	0.42
914.37	65.75	0.18	22.0	0.34
864.79	62.18	0.21	23.9	0.39
829.22	59.34	0.29	21.2	0.36
783.43	56.33	0.36	19.7	0.35
758.36	54.33	0.27	20.4	0.37
724.37	52.08	0.27	17.2	0.33
695.95	50.04	0.46	16.2	0.32
668.65	48.08	0.27	14.9	0.31
646.92	46.52	0.41	16.2	0.35
624.07	44.87	0.32	14.1	0.31
605.13	43.51	0.46	13.4	0.31
565.01	40.63	0.31	12.2	0.30
549.41	39.51	0.47	13.4	0.34
532.13	38.26	0.33	11.0	0.29
521.55	37.50	0.49	9.0	0.24
502.60	36.14	0.35	13.8	0.38
474.74	34.13	0.37	11.5	0.34
468.05	33.65	0.46	8.7	0.26
409.55	29.45	0.67	9.8	0.33
393.17	28.27	0.73	8.2	0.29
382.25	27.48	0.40	6.1	0.22
352.35	25.33	0.73	6.7	0.27
333.63	23.99	0.55	7.2	0.30
305.98	22.00	0.59	5.7	0.26
287.24	20.65	0.70	5.3	0.26
278.32	20.01	0.83	5.4	0.27
250.44	18.01	0.84	4.3	0.24
247.55	17.80	0.91	4.3	0.24
227.48	16.36	1.22	4.4	0.27
222.79	16.02	1.46	4.0	0.25
194.78	14.01	0.77	3.4	0.25
180.11	12.95	0.55	3.4	0.26
166.77	11.99	0.75	3.5	0.29
164.54	11.83	1.09	2.4	0.21
152.7[illegible]	10.98	0.67	3.7	0.34
146.76	10.55	1.17	2.4	0.23
128.41	9.23	1.83	2.1	0.22
125.19	9.00	0.59	2.2	0.25
121.74	8.75	1.29	2.0	0.23
119.65	8.60	0.78	2.0	0.24
113.18	8.14	1.12	2.0	0.24
108.55	7.83	1.19	2.0	0.26
108.62	7.81	1.24	2.1	0.27
104.85	7.54	0.96	2.2	0.28
98.50	7.08	0.72	2.0	0.28
97.30	7.00	0.93	2.0	0.29
92.21	6.63	0.84	2.0	0.3[illegible]
81.81	5.88	0.45	2.0	0.35

APPENDIX-C TRANSVERSE FORCE DATA FOR ROUGH CYLINDERS

DIAM = 4.0" k/D = 1/370 β = 1770

REYN	[illegible]	CL MAX	FR	ST
208.23	117.59	0.27	29.0	0.25
177.87	100.49	0.35	23.[illegible]	0.24
155.82	88.03	0.40	23.9	0.27
131.4[illegible]	74.[illegible]	0.3[illegible]	16.[illegible]	0.2[illegible]
116.82	67.13	0.37	15.3	0.23
105.36	59.53	0.68	13.8	0.23
[illegible]7.54	4[illegible].54	0.50	12.2	0.25
79.45	44.89	0.54	10.6	0.24
72.56	41.22	0.76	9.8	0.24
56.50	31.92	0.59	7.6	0.24
52.40	29.60	1.01	6.6	0.22
48.35	27.32	1.12	[illegible]	0.24
43.58	24.35	1.01	5.5	0.22
40.37	22.31	1.54	5.1	0.22
39.70	21.36	1.5[illegible]	4.[illegible]	0.22
32.71	13.48	1.33	4.1	0.22
29.19	16.49	1.23	3.6	0.22
27.85	15.74	1.21	3.7	0.24

DIAM = 4.0" $k/D = 1/370$ $\beta = 2362$

REYN	UMID	CLMAX	FR	ST
278.48	117.16	0.32	27.5	0.23
221.27	93.90	0.35	22.0	0.23
178.07	75.36	0.43	14.9	0.20
160.70	68.01	0.62	13.8	0.26
143.64	60.38	0.65	12.3	0.23
131.68	55.73	0.86	13.1	0.24
112.82	47.75	0.79	11.2	0.24
98.99	41.89	1.22	9.1	0.22
82.41	34.83	1.39	8.3	0.24
75.42	31.92	1.52	7.2	0.23
66.18	28.01	1.17	6.3	0.23
55.34	23.42	0.97	5.3	0.23
50.04	21.13	1.16	4.7	0.22
46.47	19.67	1.23	4.6	0.24
43.01	18.24	1.43	4.2	0.23
40.40	17.10	2.52	3.8	0.22
37.90	16.04	1.96	2.5	0.16
34.34	14.53	2.77	2.0	0.14
31.84	13.47	3.63	2.1	0.16
29.33	12.42	3.09	2.0	0.16
26.57	11.25	3.18	2.0	0.18
24.71	10.46	2.98	2.0	0.19

DIAM = 4.0" k/D = 1/370 β= 3127

REYN	CATMD	CLMAX	FR	ST
355.02	123.08	0.27	29.0	0.24
326.43	104.35	0.34	27.5	0.26
282.92	90.44	0.52	21.2	0.23
225.10	71.[illegible]	0.49	19.[illegible]	0.26
211.25	67.53	0.64	16.2	0.24
193.35	61.81	0.74	14.1	0.23
162.35	51.90	0.87	12.0	0.23
143.83	45.98	0.95	10.2	0.22
121.19	38.74	1.31	8.7	0.23
105.69	33.79	1.37	7.4	0.22
96.53	30.86	0.81	7.2	0.24
79.23	25.33	1.66	5.4	0.21
72.26	23.10	1.50	5.1	0.22
68.44	21.88	1.22	5.2	0.24
60.62	19.38	1.27	4.6	0.24
54.24	17.34	1.95	4.2	0.24
50.98	16.30	2.14	3.9	0.24
47.92	15.32	0.74	3.6	0.25
44.81	14.32	1.63	3.8	0.27
42.10	13.46	1.80	3.7	0.28

DIAM = 5.0" k/D = 1/370 β= 2704

REYN	UMTJD	CLMAX	FR	ST
237.32	98.86	0.33	22.9	0.23
259.04	95.79	0.33	23.9	0.25
215.17	79.37	0.38	21.2	0.27
234.31	75.74	[illegible]	13.7	0.26
130.81	60.86	0.55	15.3	0.23
177.37	65.78	0.77	16.2	0.25
147.48	54.54	0.81	12.2	0.22
138.67	51.28	0.78	11.7	0.23
130.22	48.15	0.86	11.0	0.23
120.61	44.60	1.24	11.0	0.25
110.59	40.90	0.99	9.2	0.22
110.31	40.79	1.08	10.0	0.25
99.53	36.31	0.86	7.9	0.21
97.94	36.22	1.02	8.1	0.22
86.88	32.13	0.76	6.3	0.20
82.94	30.67	1.26	7.2	0.24
70.50	26.07	0.62	6.3	0.24
68.70	25.41	1.28	5.5	0.22
66.08	24.44	1.42	5.3	0.22
62.55	23.13	1.30	5.3	0.23
56.23	20.30	0.33	5.0	0.24
55.23	20.43	1.48	4.6	0.23
51.68	19.11	1.04	4.4	0.23
48.34	17.38	1.52	4.4	0.25
46.65	17.25	1.45	3.9	0.23
43.90	16.23	1.57	3.9	0.24
42.52	15.72	1.40	3.6	0.23
40.11	14.33	1.37	3.8	0.26
38.63	14.28	1.13	3.3	0.23
36.52	13.51	0.94	2.8	0.20
35.49	13.12	1.34	3.6	0.27
33.37	12.30	1.07	2.4	0.19
31.65	11.70	0.95	2.6	0.22
31.54	11.66	0.94	2.3	0.20
29.86	11.04	1.39	2.3	0.21
29.81	11.02	1.30	2.3	0.21
27.90	10.32	1.27	2.3	0.22
25.54	9.45	1.35	2.1	0.22

DIAM = 5.0"   k/D = 1/370 β = 3612

REYN	UMTOD	CLMAX	FR	ST
350.59	97.51	0.37	22.0	0.23
339.97	94.13	0.38	23.9	0.25
279.67	77.78	0.47	18.4	0.24
272.16	75.36	0.49	14.9	0.20
223.86	62.26	0.80	13.4	0.22
212.20	58.75	0.64	13.1	0.22
183.59	50.83	0.96	11.5	0.23
169.27	47.08	0.84	10.0	0.21
166.16	46.00	0.95	10.0	0.22
147.70	40.90	1.04	8.9	0.22
137.47	38.24	0.95	9.2	0.22
127.39	35.27	1.11	[illegible]	0.22
119.46	33.23	1.38	7.3	0.22
117.61	32.56	1.39	7.1	0.22
105.79	29.29	1.35	6.3	0.22
96.40	26.69	1.57	5.9	0.22
88.62	24.54	1.84	5.3	0.22
88.49	24.61	1.90	5.3	0.22
78.23	21.66	1.28	5.0	0.23
72.29	20.11	[illegible]	4.6	0.23
72.07	19.95	1.87	4.2	0.21
66.06	18.37	2.31	4.2	0.23
65.35	18.09	1.86	3.9	0.22
60.93	16.87	2.29	3.9	0.23
60.61	16.86	1.55	3.9	0.23
56.99	15.35	1.56	3.7	0.24
53.48	14.81	0.76	2.2	0.15
49.70	13.76	0.66	2.0	0.15
48.28	13.43	1.30	2.2	0.16
46.76	12.95	1.00	2.1	0.16
44.18	12.23	1.38	2.0	0.17
43.84	12.19	2.47	2.2	0.18
41.27	11.48	2.05	2.2	0.19
39.58	10.96	1.42	2.0	0.18
38.99	10.84	1.99	2.0	0.19
35.81	9.96	1.60	2.1	0.21
35.78	9.90	0.77	2.1	0.22
33.23	9.24	1.11	2.2	0.24

DIAM = 5.0"   k/D = 1/370 β= 4866

REYN	UMTOD	CLMAX	FR	ST
426.64	87.68	0.41	21.2	0.24
320.37	65.34	0.80	19.7	0.20
266.59	54.28	0.87	13.4	0.24
263.81	54.22	0.35	13.1	0.24
233.49	47.54	1.15	11.0	0.23
219.26	45.06	1.17	10.4	0.23
197.83	40.23	0.97	9.8	0.24
133.52	37.57	1.46	8.9	0.24
177.84	36.55	1.14	7.4	0.20
168.21	34.25	1.77	8.1	0.24
157.32	32.33	1.49	6.6	0.21
150.66	30.97	1.20	6.9	0.22
133.94	27.53	1.68	6.6	0.24
131.05	26.68	2.08	6.0	0.22
118.65	24.38	2.00	5.3	0.22
118.00	24.03	1.53	5.3	0.22
108.51	22.10	1.80	4.7	0.21
105.96	21.78	1.97	5.3	0.25
97.62	19.88	2.32	4.1	0.21
94.24	19.37	1.97	3.9	0.20
89.11	18.14	2.49	4.1	0.22
83.95	17.25	2.52	3.7	0.21
81.35	16.56	2.57	3.9	0.23
77.56	15.94	1.72	3.4	0.22
73.24	14.91	1.61	3.9	0.25
71.05	14.60	1.97	2.0	0.14
67.59	13.76	2.09	2.1	0.15
64.98	13.35	2.04	2.2	0.16
62.58	12.74	2.48	2.1	0.17
60.51	12.44	2.31	2.0	0.16
57.82	11.77	2.74	2.0	0.17
55.12	11.33	2.60	2.0	0.17
54.64	11.12	2.23	2.0	0.18
51.73	10.63	2.16	2.0	0.19
51.62	10.51	1.92	2.1	0.20
48.60	9.90	1.84	2.0	0.21
48.30	9.93	2.24	2.0	0.20
46.83	9.53	1.97	2.0	0.21
45.68	9.39	2.08	2.0	0.21
43.81	9.00	1.44	2.0	0.22
43.75	8.90	1.47	2.0	0.23

DIAM = 6.5"　　　k/D = 1/370　　　β= 4280

REYN	UMTOD	CLMAX	FR	ST
349.20	81.57	0.33	13.7	0.24
324.61	75.95	0.34	14.3	0.24
258.[illegible]	[illegible]	0.40	14.9	0.25
252.52	59.08	0.53	13.8	0.23
209.59	49.12	0.76	12.6	0.26
196.77	45.98	1.04	11.5	0.25
172.65	40.44	1.06	9.5	0.23
158.98	37.13	1.36	8.7	0.24
149.16	34.69	1.18	7.4	0.21
131.95	30.92	1.77	8.1	0.26
123.17	[illegible]	[illegible]	[illegible]	[illegible]
106.97	25.03	1.95	5.3	0.21
97.09	22.68	1.87	4.8	0.21
94.66	22.13	1.31	4.6	0.22
86.56	20.25	2.52	5.0	0.25
83.66	19.54	2.04	4.8	0.25
78.08	18.24	2.66	4.4	0.24
76.80	17.97	2.71	3.1	0.17
68.[illegible]	16.14	[illegible]	[illegible]	[illegible]
67.30	15.73	2.91	3.9	0.25
61.57	14.41	1.63	2.0	0.14
56.32	13.16	2.31	2.1	0.18
54.84	12.83	2.16	2.0	0.15
51.86	12.11	2.25	2.1	0.17
46.97	10.97	2.25	2.1	0.19
41.20	9.62	1.94	2.2	0.23
38.80	[illegible]	[illegible]	2.1	[illegible]
36.42	8.51	1.89	2.2	0.26
34.41	8.04	1.77	2.1	0.26
31.25	7.30	0.98	2.0	0.23
29.45	6.88	0.96	2.0	0.30

DIAM = 6.5"   k/D = 1/370 β = 6242

REYN	UMTCD	CLMAX	FR	ST
545.50	57.39	0.27	20.4	0.23
510.46	82.26	0.32	19.0	0.23
416.21	[illegible]	0.41	15.7	0.23
394.04	63.12	0.47	14.5	0.23
297.99	47.74	0.37	12.3	0.27
287.07	[illegible]	0.72	10.2	0.22
245.66	39.35	1.25	10.4	0.26
244.83	39.15	1.40	9.0	0.23
203.62	32.34	1.82	7.9	0.24
179.39	23.32	1.31	11.7	0.40
[illegible]	[illegible]	1.00	[illegible]	[illegible]
143.42	22.97	1.74	5.0	0.24
137.18	22.11	1.21	4.6	0.21
127.39	20.33	2.50	4.0	0.19
124.20	19.90	2.70	4.7	0.23
115.08	13.44	2.33	3.9	0.21
113.18	13.24	2.56	3.9	0.22
105.34	16.83	3.49	4.1	0.24
103.56	15.69	3.17	[illegible]	[illegible]
95.45	15.29	3.27	3.0	0.24
95.26	15.35	2.72	3.6	0.23
79.33	[illegible]	2.40	2.1	0.18
76.06	12.28	2.15	2.0	0.16
72.95	11.51	2.31	2.2	0.19
66.68	10.75	3.00	2.1	0.20
64.30	10.38	1.95	2.1	0.20
62.06	10.03	[illegible]	2.3	[illegible]
58.84	9.43	1.82	2.1	0.22
57.76	9.30	2.68	2.3	0.25
56.65	[illegible]	[illegible]	2.0	0.23
54.40	8.72	1.17	2.0	0.23
53.37	8.60	2.39	2.1	0.24
51.65	8.27	1.37	2.0	0.25
50.06	8.07	1.31	2.0	0.25
48.50	7.77	1.77	[illegible]	0.26
46.44	7.43	1.25	2.0	0.27
39.68	6.39	0.67	2.0	0.32

DIAM = 6.5"   k/D = 1/370 β = 8313

REYN	UHTOD	CLMAX	FR	ST
709.25	85.32	0.28	27.5	0.32
633.00	76.14	0.38	18.4	0.24
582.16	70.03	0.33	17.3	0.25
501.81	60.36	0.59	14.9	0.25
491.97	59.18	0.62	16.7	0.23
409.15	49.22	0.72	11.9	0.22
365.28	43.94	1.08	12.8	0.29
312.42	37.58	1.51	8.2	0.22
306.84	36.91	1.63	3.9	0.24
269.43	32.41	1.59	8.0	0.25
235.61	28.36	1.45	6.5	0.23
230.21	27.69	2.33	6.1	0.22
206.75	24.37	1.97	6.0	0.21
173.27	20.83	3.05	4.4	0.21
159.66	19.20	1.85	4.6	0.24
155.55	13.71	3.36	4.1	0.22
136.61	16.43	2.69	3.7	0.22
134.23	16.15	2.89	3.8	0.23
125.57	15.15	2.51	3.2	0.21
121.83	14.66	2.48	3.7	0.25
111.25	13.38	3.07	2.3	0.17
107.24	12.90	2.95	2.1	0.18
102.25	12.30	2.63	2.0	0.16
92.11	11.08	2.80	2.1	0.19
90.64	10.90	2.93	2.2	0.20
34.25	10.14	2.92	2.1	0.21
83.63	10.06	2.94	2.2	0.22
78.53	9.45	2.79	2.1	0.22
78.45	9.44	2.95	2.3	0.25
74.47	8.96	2.78	2.3	0.25
72.41	3.71	2.24	2.0	0.24
68.46	8.24	2.05	2.0	0.25
68.13	8.20	2.94	2.4	0.29
64.02	7.70	1.97	2.0	0.26
61.80	7.43	2.27	2.0	0.27
59.99	7.10	1.37	2.0	0.28
57.85	6.96	2.10	2.0	0.29

DIAM = 8.0"   k/D = 1/370 β= 7125

REYN	UMTOD	CLMAX	FC	ST
453.15	64.93	0.59	15.7	0.26
397.19	55.73	0.78	12.5	0.23
308.56	43.25	1.51	10.3	0.25
290.37	40.70	0.56	9.7	0.24
273.27	38.34	1.70	9.8	0.26
243.50	34.64	0.32	8.1	0.22
227.01	31.35	2.33	7.5	0.24
222.07	32.53	1.10	8.1	0.25
216.46	30.37	1.73	8.1	0.27
200.12	28.39	1.39	6.6	0.23
186.45	26.14	1.42	5.4	0.20
185.54	26.09	2.19	6.0	0.25
176.11	24.71	1.97	5.5	0.27
155.00	21.94	2.00	4.7	0.22
147.56	20.63	1.65	4.8	0.23
135.08	18.95	1.82	3.7	0.20
117.26	16.45	1.71	3.6	0.23
114.39	16.03	2.08	3.7	0.23
113.16	15.88	2.01	4.1	0.25
106.38	14.91	2.51	3.6	0.24
99.52	13.95	2.49	2.0	0.15
96.43	13.63	2.56	4.5	0.33
92.20	12.92	2.73	2.0	0.16
91.01	12.35	2.54	2.0	0.16
88.14	12.37	2.74	2.0	0.16
85.29	11.97	2.69	2.0	0.17
83.94	11.77	2.80	2.1	0.18
78.95	11.06	2.59	2.0	0.18
77.33	10.84	2.76	2.2	0.20
75.83	10.64	2.76	2.1	0.22
71.29	9.99	2.80	2.2	0.22
70.53	9.90	2.53	2.2	0.22
67.51	9.47	2.78	2.2	0.23
66.15	9.27	2.55	2.2	0.24
63.47	8.91	2.53	2.2	0.25
61.36	8.60	2.54	2.1	0.24
58.80	8.25	2.13	2.1	0.26
58.23	8.17	2.54	2.4	0.30
57.25	8.03	2.62	2.0	0.24
54.70	7.67	1.32	2.0	0.25
53.60	7.51	1.94	2.2	0.23
49.95	7.00	1.64	2.0	0.23
48.20	6.76	1.44	2.3	0.30
45.29	6.36	1.59	2.3	0.21
44.07	6.19	0.96	2.2	0.25
41.29	5.79	0.34	2.3	0.25

DIAM = 8.0"   k/D = 1/370 β = 14,050

REYN	UYTOD	CL MAX	FR	ST
824.34	[illegible]	0.72	13.9	0.24
817.58	53.17	0.69	14.1	0.24
720.17	51.34	[illegible]	13.1	0.26
716.22	50.96	0.85	13.4	0.26
637.40	45.35	1.06	14.1	0.31
630.64	44.77	1.29	9.0	0.29
571.52	40.67	0.97	9.2	0.23
564.19	40.14	1.72	7.7	0.19
515.77	36.70	1.23	8.3	0.23
507.39	35.14	2.07	7.2	0.20
470.16	33.45	1.75	7.3	0.23
428.19	30.47	1.92	6.4	0.21
402.27	28.62	1.80	6.8	0.24
374.33	[illegible]	2.04	5.9	0.21
347.51	24.73	1.38	5.5	0.22
304.24	21.65	2.29	5.3	0.25
242.54	17.29	2.24	5.1	[illegible]
216.35	15.39	2.59	2.7	0.17
215.00	15.30	3.15	3.5	0.24
133.13	13.03	2.53	2.2	0.17
160.56	11.43	3.39	2.0	0.17
145.60	10.36	2.35	2.0	0.19
139.65	9.94	1.92	2.1	0.21
130.09	9.26	2.13	2.3	0.25
115.27	8.20	3.13	2.5	0.31
109.43	7.79	2.98	2.2	0.23
105.83	7.53	1.83	2.1	0.28
103.14	7.34	2.29	2.3	0.31
99.99	7.12	2.05	2.0	0.29
98.32	7.07	2.04	2.0	0.26
96.06	6.84	1.89	2.1	0.31
92.11	6.55	1.71	2.0	0.31
89.62	6.38	1.53	2.0	0.32
89.39	6.36	1.40	2.0	0.32
88.94	6.33	1.21	2.0	0.32
87.56	6.23	1.23	2.0	0.33
32.84	5.39	1.57	2.0	0.34
77.14	5.49	0.62	2.0	0.30
73.57	5.24	0.72	2.0	0.29

DIAM = 4.0"   k/D = 1/195 β= 1537

REYN	UPTCD	CLMAX	FR	ST
179.73	117.00	0.49	23	0.24
167.94	109.31	0.34	28	0.25
154.23	100.39	0.32	25	0.25
152.76	99.45	0.45	21	0.21
137.87	89.73	0.33	20	0.22
131.49	85.59	0.38	20	0.23
125.11	81.44	0.35	19	0.23
109.47	71.26	0.53	17	0.24
107.79	70.16	0.68	16	0.22
94.80	61.70	0.59	14	0.23
93.23	60.69	0.91	14	0.24
88.06	57.32	0.35	13	0.22
78.20	50.90	1.18	11	0.21
77.47	50.43	0.84	11	0.23
73.14	47.61	0.76	11	0.23
64.96	42.28	0.90	10	0.23
62.26	43.33	0.64	10	0.24
58.90	38.34	0.83	9	0.25
55.05	35.83	0.88	9	0.24
54.57	35.52	1.05	8	0.23
49.85	32.45	0.86	8	0.25
47.88	31.17	1.18	9	0.26
47.01	30.60	0.83	7	0.22
44.17	28.75	1.42	8	0.28
42.59	27.72	0.99	7	0.25
41.66	27.12	1.48	7	0.27
39.29	25.57	1.39	7	0.26
37.77	24.59	1.09	5	0.21
35.92	23.38	1.55	6	0.25
34.26	22.30	1.39	5	0.24
33.68	21.93	1.89	6	0.26
31.57	20.55	2.04	6	0.27
29.59	19.26	1.41	4	0.23
29.16	18.98	1.78	4	0.23
28.19	18.35	2.30	4	0.23
26.55	17.34	2.15	4	0.24
26.56	17.29	2.71	4	0.24
25.22	16.41	2.27	4	0.26
23.82	15.50	2.20	4	0.24
23.77	15.47	2.85	4	0.25
22.66	14.75	2.40	2	0.16
21.89	14.25	2.10	2	0.17
20.62	13.42	2.85	2	0.15
20.07	13.08	2.91	2	0.16
18.89	12.29	2.94	2	0.16
18.13	11.30	3.49	2	0.19
16.53	10.76	2.53	2	0.19
16.05	10.45	3.21	2	0.22
15.08	9.32	2.31	2	0.20
14.55	9.47	2.91	2	0.25
13.56	8.32	2.87	2	0.23
13.17	8.57	2.74	2	0.23
12.01	7.31	2.14	2	0.26
11.86	7.72	2.62	2	0.31
10.53	6.85	0.97	2	0.29

DIAM = 4.0"   k/D = 1/195 β = 2350

REYN	UMTDD	CLMAX	FP	ST
291.58	123.[illegible]	0.[illegible]4	29.0	0.24
290.98	124.61	0.23	27.5	0.22
253.[illegible]	108.[illegible]	0.[illegible]	25.[illegible]	0.23
225.27	96.47	0.49	22.9	0.24
210.47	89.08	0.43	21.2	0.24
19[illegible]	[illegible]	0.53	19.7	0.23
179.64	76.13	0.43	20.4	0.27
172.71	73.90	0.55	14.9	0.20
154.62	65.92	0.62	14.9	0.23
143.42	61.42	0.83	14.5	0.23
129.10	5[illegible]	0.98	12.5	0.23
123.22	52.77	0.68	12.8	0.24
108.95	46.65	0.95	12.0	0.26
100.97	43.27	0.69	10.4	0.23
99.18	42.47	0.78	9.7	0.23
97.09	41.09	1.07	10.4	0.25
92.57	39.64	1.01	9.6	0.24
82.95	35.10	1.12	7.8	0.22
78.00	33.01	1.25	7.2	0.22
74.84	32.05	0.96	9.7	0.27
65.49	27.72	1.89	6.6	0.24
65.33	27.77	1.19	5.7	0.21
61.21	25.91	1.69	5.7	0.22
57.76	24.73	1.47	5.2	0.21
52.30	22.14	0.91	4.6	0.22
51.69	22.14	1.55	5.1	0.23
49.29	23.77	1.44	4.8	0.24
45.14	19.10	2.21	4.4	0.23
43.75	18.74	2.55	4.3	0.23
42.22	17.87	2.54	4.3	0.24
40.30	17.26	2.40	3.7	0.21
39.49	16.71	2.61	4.3	0.26
37.22	15.75	2.43	3.6	0.23
36.71	15.72	1.67	3.5	0.22
33.[illegible]	[illegible]	1.25	2.[illegible]	0.16
33.12	14.02	1.95	3.6	0.27
31.46	13.47	1.56	[illegible].0	0.15
31.19	13.19	2.68	2.1	0.16
29.96	12.33	1.17	2.0	0.16
29.12	12.41	2.53	2.1	0.17

DIAM = 4.0"   k/D = 1/195 β= 3070

REYN	LMTOD	CLMAX	FP	ST
419.41	132.61	0.28	[illegible]	0.22
350.49	114.15	0.32	25.0	0.22
347.22	110.14	0.34	[illegible]	0.21
296.88	90.84	0.30	19.7	0.22
286.81	93.42	0.34	22.0	0.24
258.96	83.03	0.48	18.4	0.22
233.00	75.89	0.53	19.7	0.26
228.49	72.35	0.52	17.2	0.24
198.03	62.71	0.67	12.5	0.20
188.82	61.50	0.87	16.2	0.26
172.34	54.70	0.83	[illegible]	0.22
153.03	48.46	1.21	11.5	0.24
150.85	49.13	0.94	11.5	0.23
133.76	43.57	0.95	11.2	0.20
130.27	41.25	0.91	9.0	0.22
114.20	37.20	1.09	9.8	0.26
104.96	33.21	1.39	7.1	0.21
103.73	33.73	1.69	8.2	0.24
87.72	27.80	1.32	6.7	0.24
86.34	28.12	1.57	6.4	0.23
82.27	26.05	1.13	5.2	0.20
76.70	25.63	2.06	5.4	0.21
72.94	23.10	1.43	5.1	0.22
69.48	22.76	2.32	5.2	0.23
65.85	20.35	1.55	5.1	0.24
62.55	20.37	1.90	4.5	0.22
58.20	19.18	2.40	[illegible]	0.22
56.94	18.03	2.84	4.1	0.23
55.26	17.20	2.31	4.3	0.25
50.42	15.59	2.37	[illegible]	0.24
49.74	15.75	2.96	2.4	0.15
47.11	15.34	2.50	3.2	0.25
46.12	14.50	1.82	2.3	0.15
42.80	13.55	1.40	2.2	0.16
40.[illegible]	13.81	1.22	2.4	0.16
40.15	13.09	2.12	2.1	0.16
37.20	11.78	1.44	2.0	0.17
37.11	12.10	2.45	2.1	0.17
34.38	11.20	2.52	2.1	0.20
31.85	10.38	2.61	2.1	0.21
29.43	9.58	2.46	2.1	0.23

DIAM = 5.0"   k/D = 1/195 β= 2550

REYN	LMTOL	CLMAX	FR	ST
243.91	55.54	0.40	22.9	0.24
220.26	66.34	0.38	16.4	0.21
200.56	71.55	0.42	19.0	0.24
170.36	66.67	0.62	14.1	0.21
170.05	66.61	0.56	15.3	0.23
147.60	57.66	0.83	11.0	0.19
139.24	54.24	0.97	13.4	0.25
125.14	49.32	1.00	10.4	0.21
112.15	43.96	0.74	9.8	0.22
101.72	39.37	0.86	7.9	0.20
92.66	36.30	1.30	10.0	0.24
91.02	35.08	1.27	7.5	0.21
81.90	32.09	1.61	7.8	0.24
80.35	31.04	1.28	6.6	0.21
70.16	27.50	0.68	5.8	0.21
70.02	27.43	1.05	6.2	0.23
65.72	25.70	1.17	5.5	0.21
63.10	24.72	1.06	5.9	0.24
62.03	24.39	1.51	5.4	0.22
58.03	22.75	1.61	4.6	0.20
57.82	22.65	1.83	5.3	0.24
51.03	20.31	2.10	4.2	0.21
49.94	19.36	2.08	4.5	0.23
46.35	18.17	2.62	4.1	0.22
45.02	17.64	2.36	4.1	0.23
42.06	16.49	2.31	3.9	0.24
40.72	15.95	2.40	4.0	0.25
37.70	14.77	2.38	3.9	0.26
35.37	13.86	0.86	3.1	0.22
34.42	13.48	1.57	3.1	0.19
32.83	12.37	1.56	2.4	0.19
32.30	12.35	2.10	2.0	0.16
31.47	12.33	2.06	3.0	0.16
29.34	11.70	2.05	2.0	0.17
28.30	11.51	2.51	2.0	0.17
26.98	10.57	2.35	2.0	0.19
24.74	9.09	2.20	2.0	0.21
23.14	9.08	1.95	2.1	0.23
20.04	7.35	1.18	2.0	0.26

DIAM =5.0" k/D = 1/195 β=3612

PEYN	UMTOD	CLMAX	FR	ST
356.58	98.73	0.23	26.2	0.27
268.01	74.21	0.46	16.2	0.22
200.65	55.56	0.91	15.3	0.28
164.86	45.65	1.20	10.4	0.23
129.61	35.89	1.38	7.6	0.21
98.22	27.20	1.18	6.1	0.22
76.35	21.28	1.68	4.7	0.22
67.00	18.55	2.45	4.2	0.23
58.44	16.18	2.65	3.7	0.23
52.46	14.53	2.37	3.5	0.24
46.94	13.00	1.78	2.1	0.16
42.34	11.72	2.63	2.1	0.18
39.25	10.87	2.43	2.0	0.19
35.78	9.90	2.57	2.1	0.22
32.54	9.01	[illegible]	2.0	[illegible]
31.25	8.66	1.92	2.0	0.23

DIAM = 5.0" k/D = 1/195 β= 5436

REYN	LYTOD	CLMAX	FR	ST
547.45	100.71	0.41	23.9	0.24
506.30	93.24	0.32	21.1	0.23
429.75	73.[illegible]	0.55	16.7	0.21
418.68	77.02	0.70	17.8	0.23
362.09	66.61	0.68	16.2	0.24
355.50	65.39	0.72	14.9	0.23
294.74	54.22	1.13	11.5	0.21
293.79	54.03	0.97	11.0	0.20
254.97	46.90	0.96	10.0	0.23
228.97	42.12	0.99	9.0	0.21
223.68	41.[illegible]	1.20	8.[illegible]	0.22
203.90	37.52	1.60	7.5	0.20
181.32	33.36	1.39	8.2	0.25
177.02	32.[illegible]	1.90	7.0	0.22
163.50	30.10	1.42	7.0	0.25
152.29	28.01	2.04	6.3	0.24
146.45	26.94	1.35	5.9	0.22
132.83	24.44	2.53	5.3	0.22
120.66	22.16	2.37	5.[illegible]	0.23
106.31	19.65	2.93	4.5	0.23
100.51	18.49	2.46	4.2	0.23
97.25	17.[illegible]	2.69	4.2	0.23
89.36	16.44	2.65	3.9	0.24
86.40	15.93	1.30	4.2	0.25
81.67	15.02	1.30	3.4	0.23
77.86	14.32	2.14	2.0	0.14
74.38	13.72	2.07	2.0	0.15
69.41	12.77	2.[illegible]7	2.1	0.17
68.30	12.56	2.93	2.1	0.17
64.41	11.84	2.91	2.1	0.18
62.07	11.42	2.48	2.0	0.17
61.04	11.23	2.76	2.1	0.19
57.63	10.60	2.75	2.1	0.20
57.62	10.60	2.92	2.1	0.20
53.83	9.90	2.[illegible]	2.1	0.21
53.51	9.84	2.86	2.1	0.21
50.38	9.27	2.69	2.1	0.22
49.52	9.12	2.42	2.2	0.24
49.47	9.10	2.21	2.0	0.22
47.24	8.69	2.70	2.0	0.24
44.[illegible]0	8.[illegible]4	2.55	2.0	0.25
44.52	8.19	2.30	2.0	0.25
42.50	7.[illegible]	1.[illegible]	2.0	0.26
39.93	7.34	1.73	2.0	0.28

DIAM = 6.0" k/D = 1/195 β= 3587

REYN	UMTCD	CLMAX	FR	ST
312.48	87.11	0.36	21.2	0.24
287.72	80.59	0.43	17.8	0.22
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
218.65	61.25	0.49	14.1	0.23
185.19	51.63	0.85	11.5	0.22
[illegible]	[illegible]	[illegible]	10.6	[illegible]
157.97	44.04	1.05	10.0	0.23
156.45	43.62	0.55	9.2	0.21
136.27	37.99	1.23	8.9	0.23
134.09	37.56	1.38	8.1	0.22
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
105.38	29.52	2.47	7.1	0.24
92.84	25.38	1.91	5.6	0.22
92.40	[illegible]	2.01	5.5	0.21
82.10	22.89	1.85	5.3	0.23
81.25	22.75	1.95	5.0	0.22
73.65	20.36	2.68	4.7	0.23
67.99	19.04	2.30	3.9	0.20
[illegible]	17.31	[illegible]	4.5	0.25
60.15	16.35	2.75	3.7	0.22
56.23	15.68	2.60	3.8	0.24
[illegible]	14.76	2.59	3.4	[illegible]
49.42	13.78	2.23	4.1	0.30
46.44	13.01	2.24	2.1	0.16
44.41	12.38	2.90	2.1	0.17
41.50	11.62	2.85	2.1	0.18
37.56	10.47	[illegible]	2.2	0.21
37.16	10.41	2.81	2.2	0.21
34.67	9.67	2.37	2.3	0.23
34.20	9.53	[illegible]	2.2	0.23
31.98	8.91	2.06	2.2	0.25
31.94	8.95	2.20	2.2	0.25
29.40	8.20	2.09	2.1	0.26
28.84	8.08	2.05	2.2	0.27
27.74	[illegible]	[illegible]	[illegible]	[illegible]
26.50	7.42	1.52	2.1	0.29
26.15	7.29	1.54	2.0	0.28
24.23	6.77	[illegible]	2.0	0.30
24.13	6.76	0.95	2.0	0.30

DIAM =6.0" k/D = 1/195 β=5347

REYN	UMTOD	CLMAX	FR	ST
451.47	84.44	0.39	19.7	0.23
397.75	74.39	0.45	15.3	0.21
293.74	54.94	0.84	12.2	0.22
241.73	45.21	1.00	9.5	0.21
133.44	34.51	1.33	7.9	0.23
149.82	28.02	1.86	6.3	0.23
132.66	24.81	2.17	5.4	0.22
122.66	22.94	2.12	4.6	0.20
98.29	18.38	2.90	3.9	0.21
86.09	16.10	2.92	3.6	0.23
71.61	13.39	1.63	2.1	0.16
64.42	12.05	2.90	2.0	0.17
57.58	10.77	3.16	2.0	0.19
53.02	9.92	2.98	2.0	0.20
49.60	9.28	2.97	2.1	0.23
45.31	8.47	2.70	2.3	0.27
41.46	7.76	2.29	2.2	0.29
39.57	7.40	1.72	2.0	0.28
35.84	6.70	1.62	2.0	0.30
32.98	6.16	1.01	2.0	0.33

DIAM = 6.0"   k/D = 1/195 β = 7040

PEYN	UMTOD	CLMAX	FR	ST
630.10	90.00	0.36	19.7	0.22
591.64	83.59	0.32	18.4	0.22
469.08	[illegible]	0.50	14.9	0.22
420.94	60.12	0.57	13.8	0.23
338.88	54.94	0.95	12.8	0.23
338.23	48.91	1.04	10.6	0.22
331.33	46.82	0.86	11.2	0.24
289.01	40.83	1.23	9.3	0.23
246.30	35.33	1.34	8.1	0.23
238.11	34.01	1.65	7.5	0.22
216.21	30.55	[illegible]	6.7	0.22
197.93	28.28	1.36	6.6	0.24
171.02	24.43	2.45	5.1	0.21
146.56	20.71	2.70	[illegible]	0.23
151.11	21.58	1.37	5.3	0.25
134.78	19.25	2.86	4.5	0.23
129.22	18.26	3.08	4.4	0.24
113.48	16.21	2.91	3.9	0.24
112.43	15.[illegible]	2.48	3.5	0.22
98.73	13.95	2.65	2.1	0.15
90.27	12.75	2.71	1.9	0.15
80.76	11.41	2.98	2.2	0.17
78.02	11.14	1.65	2.1	0.19
70.65	9.98	3.28	2.0	0.20
71.16	10.16	1.60	2.0	0.20
66.84	9.55	2.45	2.1	0.22
64.13	9.06	2.66	[illegible]	0.24
62.86	8.98	2.57	2.2	0.24
59.63	8.52	2.75	2.3	0.27
58.61	8.23	2.04	2.1	0.27
55.50	7.93	2.64	2.3	0.28
54.39	7.76	2.47	2.0	0.25
52.34	7.48	2.32	2.1	0.25
51.25	7.24	2.33	1.9	0.27
49.76	7.1[illegible]	[illegible]	2.0	0.26
48.74	6.87	1.91	2.1	0.31
44.42	6.27	1.58	1.9	0.31
42.67	6.03	0.89	2.0	0.34

DIAM = 7.0"   k/D = 1/195 β= 4666

REYN	UMTOD	CLMAX	FR	ST
370.62	75.44	0.40	20.4	0.26
329.29	69.66	0.66	15.7	0.24
277.6[illegible]	56.51	0.94	14.5	0.24
258.21	54.62	0.97	14.1	0.26
222.76	47.75	1.22	11.5	0.24
212.85	45.92	1.50	13.3	0.31
174.47	36.91	1.83	8.5	0.23
154.71	33.16	2.01	7.4	0.22
134.42	28.44	1.69	5.8	0.20
115.39	24.41	2.25	5.2	0.21
110.17	23.62	2.50	5.6	0.24
89.91	19.02	2.28	3.9	0.21
86.66	18.58	2.67	3.0	0.27
75.91	16.35	3.30	3.8	0.24
65.71	13.90	2.24	3.4	0.25
64.42	13.81	2.72	2.2	0.16
57.76	12.33	2.96	2.0	0.16
56.92	12.04	3.00	2.1	0.18
50.91	10.77	[illegible]	2.1	0.12
50.42	10.31	3.01	2.3	0.21
47.50	10.18	2.76	2.3	0.22
44.91	9.59	2.75	2.1	0.22
42.00	9.00	2.93	2.3	0.26
41.50	8.78	1.90	2.3	0.26
38.25	8.19	2.70	2.2	0.27
37.42	7.92	2.19	2.1	0.27
35.81	7.63	2.44	2.1	0.27
33.70	7.13	1.87	2.0	0.29
33.69	7.22	1.39	2.1	0.30
31.51	6.75	1.60	2.1	0.30
30.99	6.56	0.50	2.0	0.31
29.07	6.25	1.34	2.1	0.34
26.52	5.69	0.42	2.0	0.35

DIAM = 7.0" k/D = 1/195 β= 7245

REYN	UMTOD	CLMAX	FP	ST
536.26	74.74	0.52	13.4	0.25
459.92	63.02	0.77	13.9	0.22
387.30	[illegible]	1.31	13.1	[illegible]
362.20	49.64	1.48	11.5	0.23
296.60	41.34	1.33	9.0	0.22
273.33	[illegible]	[illegible]	8.6	[illegible]
216.10	29.62	1.95	8.1	0.27
215.62	30.11	1.72	7.2	0.24
189.98	26.04	2.44	5.9	0.22
166.94	23.27	2.26	6.1	0.26
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
142.56	19.37	3.04	4.3	0.22
132.57	18.17	3.15	4.3	0.24
108.13	[illegible]	[illegible]	3.4	0.23
107.26	14.95	2.62	2.1	0.14
93.13	12.98	2.75	2.1	0.16
92.42	12.67	3.21	2.1	0.17
79.26	11.05	2.60	2.0	0.18
79.25	[illegible]	[illegible]	[illegible]	[illegible]
69.99	9.59	3.43	2.2	0.23
69.75	9.72	3.21	2.2	0.22
65.23	[illegible]	[illegible]	2.2	0.25
62.42	8.70	3.17	2.0	0.23
60.13	8.24	2.63	2.3	0.28
57.07	7.95	2.70	2.4	0.30
54.39	7.45	2.55	2.2	0.29
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
51.82	7.10	2.22	2.1	0.29
51.49	7.13	1.71	2.1	0.29
[illegible]	[illegible]	1.14	2.1	[illegible]
46.28	6.34	0.81	2.0	0.31

DIAM =7.0"   k/D = 1/195 β=9500

REYN	UMTCD	CLMAX	FR	ST
709.56	74.23	0.51	15.4	0.25
543.41	57.21	0.91	14.1	0.25
439.99	46.22	1.23	10.6	0.23
381.27	40.14	1.98	9.8	0.24
317.47	33.42	1.37	7.1	0.21
250.82	26.41	2.40	5.9	0.22
216.79	22.32	2.09	5.5	0.23
185.92	19.57	2.83	4.3	0.22
159.84	16.33	3.58	3.7	0.22
141.65	14.91	2.59	3.7	0.25
123.32	13.14	3.34	2.1	0.16
103.18	10.30	2.59	2.0	0.19
89.54	9.43	2.70	2.0	0.21
82.19	8.65	3.04	2.1	0.25
76.52	8.06	3.10	2.1	0.27
70.37	7.41	2.42	2.1	0.28
65.53	6.90	1.86	2.0	0.29
60.51	6.37	2.95	2.0	0.32
53.65	5.65	1.10	2.0	0.35

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